Biomass or batteries

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The role of three technological innovations in the energy transition

Jan Hessels Miedema

Colophon

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Biomass or batteries

The role of three technological innovations in the energy transition

PhD thesis

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by

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in Leeuwarden

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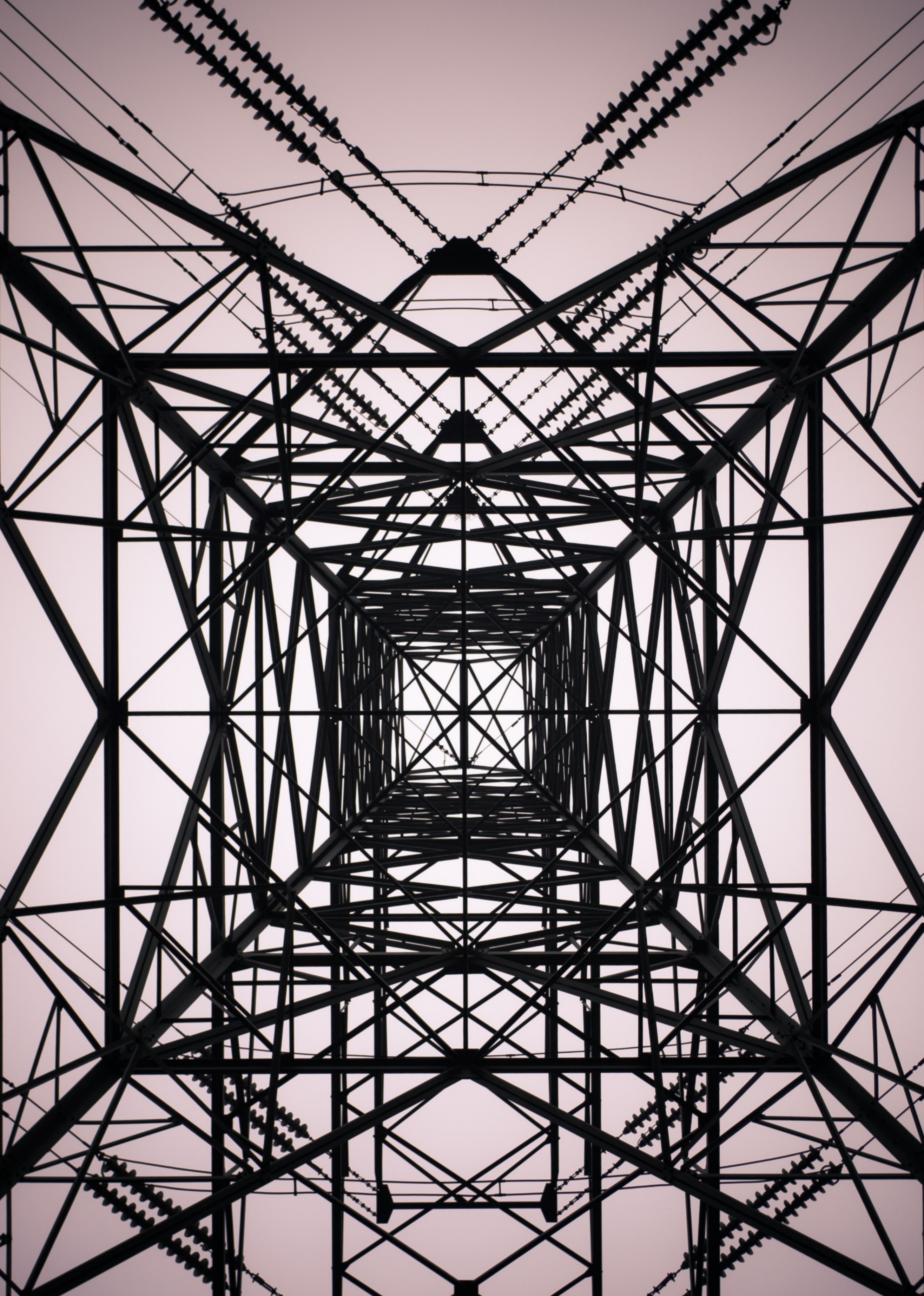
Preface



When I aimed to finish my master degree in Energy and Environmental Sciences at the University of Groningen at the end of 2011, I ended up having the same discussion with my wife as roughly two and a half years before, when I finished my bachelor degree in Environmental Science at the Van Hall Larenstein. “What are you gonna do with your life?”. Whilst I studied systems and scenarios, I found out that in life only one scenario can be lived; thus, at a certain point one has to choose a direction. After the “unilateral” agreement, with my wife, that I wasn’t welcome home if I didn’t make sure that, Henk Moll, my supervisor during my master thesis, knew I wanted a PhD position, I made sure he did. Sadly, the few positions available were already given out. However, about two months later a position became available and, partially due to the interest I had shown before, I ended up as a PhD student in April 2012.

Almost seven years later my thesis lies before you. It was a bumpy road, with ecstatic highs and incredible lows, challenging my intellectual abilities and mental perseverance. I owe a number of people my gratitude for their support during those seven years; there is, however, not enough space in this preface to name all the people who helped me, in every way possible. Still, there are a few people that I specifically want to thank. First of all, my promotor Henk Moll, for being bold enough to give me this position, whilst knowing that I had gone and was still going through the most challenging years of my life together with my wife, who was, at that time, recently diagnosed with a diffuse astrocytoma. Thank you for giving me the space I needed, and for having confidence in me bringing this journey to a successful end. Aside from this, I’m grateful that you continuously challenged my intellectual abilities and gave me the opportunity to further develop myself. Second, my co-promotor Henny van der Windt, who showed vast quantities of patience, over the years, in widening my technical perspectives towards a more general understanding of the importance of, among other factors, our society when thinking about system change. Third, René Benders, for developing similar models as I did in order to confirm my results, especially in the first years of my PhD trajectory. Your critical notions related to my results and subsequent interpretation have substantially contributed to this thesis.

In addition, to my supervisors there are a few others that I want to mention. Once in a while, during my PhD trajectory, I tended to joke about my “traditional” marriage, since my wife always makes me the best sandwiches one can imagine for lunch. Sanderine Nonhebel was the only one connecting the dots when she asked me if everything was all right, at the moment she noticed me buying lunch in the canteen, instead of bringing my own. In addition, thank you Sanderine, for always taking the time to have some coffee and provide me with motivating words in my times of need and pointing out the opportunity to participate in the best international conference ever. Against my expectations, I made two friends for life at this conference, David Alejandro Zambrana Vasquez and René Buffat. Anyone who sends me roughly two kilograms of Swiss chocolate (where weight and shipping cost are optimised) has my loyalty. Furthermore, I want to thank Ton Schoot Uiterkamp, especially during the last few years, where we shared a room in the Energy Academy Building. I’m grateful for the talks that we had about science and the future of our planet, but I am even more grateful for you sharing some of your life experience with me when this was appropriate or needed. Additionally, I would like to thank Annemiek Huizinga for helping me out with a lot of organisational questions and obviously for extending my rights as a staff member after my contract had finished. Even though some doors literally got locked for me, at least I could always get free coffee. Furthermore, I would like to thank my paranymphs, Ron de Vrieze and Gideon Laugs. Ron and I found that we had more in common than I initially thought, given our age difference and educational background. Thank you for our conversations, for me it contributed to determining what is actually important in life. Gideon, my officemate for several years. Thank you for listening to obscure music with me for about five years in a row; what a relief that we ended up with each other! Our musical preference has often resulted in strange looks and remarks from people questioning whether we were able to work productively whilst listening to the genius of, for example, Devin Townsend. One of the highlights for me was that you were willing to "neglect" your children by picking them up late from kindergarten, since you helped me jumpstart my car (more than once), in order to get home safely. Besides that, I want to thank everyone at IVEM for always making me feel at home and giving me the opportunity and trust to start a new job as a lecturer in Environmental Physics at the Van Hall Larenstein, University of Applied Sciences in Leeuwarden before the end of my PhD. Sometimes one has to grab opportunities when they present themselves. Therefore, I also want to express my gratitude towards my colleagues in Leeuwarden for giving me the time and space to finish my PhD thesis. Thank you for letting me be a part of your team at the Environmental Science department. I'm looking forward to many more years. As well as my colleagues, I want to thank the third year students of the module "Adviesbureau voor duurzame oplossingen" in 2017-2018, for thinking with me about possible sustainable solutions for the energy transition. In addition, I want to thank Cor Herder for reading parts of this manuscript and for providing useful advice on grammar and spelling.

Finally, I owe a lot to my family. My father, for passing the same "defects" on to me, as he inherited from his father, which contributed to me becoming a lecturer. Besides that, he motivated me to work harder by arguing that he did think I would get my high school degree, but probably not in the regular time. At that time he wasn't right, since I did graduate without delay, but these words still echoed in my mind when my discipline and perseverance were tested during this PhD journey. My mother, for knowing me without words being spoken, and for knowing me when words were being spoken on the phone, sometimes for hours during the good and the bad times of this whole experience. To my sister, who is living in Bolivia: I'm proud of what you achieved so far and I know the same holds for you, when it comes to me. "Los dos estamos tratando de contribuir a un mundo mejor a nuestra manera." Both my parents in law, for always showing their interest in what I was doing and, for being there for me and my wife in our times of need. My father in law for providing me with the famous words "it komt dochs altyd oars dan asto tinkst", when things didn't go as planned. Furthermore, I want to thank my brother in law Danny Boonstra for designing the cover art for this dissertation.

Most of all I owe my wife, who I cherish and adore, a lot. In order to express this in the best way I can, I will finalise this preface in Frisian.

Ik draach dit boek op aon myn frau Marjet, myn foarbyld, om't ik nea ien sjoen ha mei sa'n bjusterbaarliik trochsettingsfermogen. Nettsjinsteande dat hja dat sels lang net altyd sa sjocht, wit ik fêst dat ik nea safier kommen wie as sy net altyd foar my klear stie; mei ynspiraasje, in harkjend ear, wurden fan motivaasje, bôle foar wilens it skoft, of in skop foar myn bealch. Do bist myn alles.

Sincerely,

Jan Hessels Miedema

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List of abbreviations

AD	Anaerobic digestion
BAU	Business as usual
BC	Best case
BEV	Battery electric vehicle
BFB	Bubbling fluidised bed
CHP	Combined heat and power
$CO_{2\ eq.}$	Carbon dioxide equivalent
CO_2	Carbon dioxide
db	Dry basis
DSO	Distribution system operator
EBN	Energiebeheer Nederland
ECN	Energy research centre of the Netherlands
EE	Energy efficiency
EJ	Exajoule
EPBD	Energy performance of buildings directive
ER	Energy ratio
EU	European union
GHG	Greenhouse gas
GJ	Gigajoule
Gt	Gigaton
GTS	Gasunie transport services
GW	Gigawatt
ha	Hectare
HEV	Hybrid electric vehicle
HFO	Heavy fuel oil
ICE	Internal combustion engine
ILUC	Indirect land use change
km	Kilometre
kt	Kiloton
kWh	Kilowatt-hour
LCA	Life cycle analysis
Li_2CO_3	Lithium carbonate
Li-Ion	Lithium-ion
Mha	Million hectare
MILENA	Biomass gasification technology developed by ECN optimized for SNG
MJ	Megajoule
MLP	Multi-level perspective
Mt	Megaton
Mtoe	Megaton oil equivalent
MW	Megawatt
MW_e	Megawatt electric
NAM	Nederlandse Aardolie Maatschappij
NLs	Netherlands

NO_x	Nitrogen oxides
PHEV	Plug-in hybrid electric vehicle
PJ	Petajoule
ppm	Parts per million
R&D	Research and development
RED	Renewable energy directive
SNG	Synthetic natural gas
SO_x	Sulphur oxides
t	Ton (i.e. 10^3 kg)
TIS	Technological innovation system
tkm	Ton kilometre
TOP	Torrefaction and pelleting
TSO	Transmission system operator
US	United States
wb	Wet basis

1

Introduction

"The secret of change is to focus all of your energy, not on fighting the old, but on building the new".

-Socrates-

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Q8
Oils

1.1 General introduction

Humanity is on the verge of an energy transition, during which society gradually shifts from a dependency on fossil energy to different forms of renewable energy. This can be illustrated with global data from REN21 (2017) which shows that the decade from 2006 until 2016 has shown an exponential increase in installed capacity of solar photovoltaics and wind power. In addition, other forms of renewable energy technology (i.e. biomass conversion, geothermal, hydropower, ocean energy and concentrating solar thermal power) also show increases in installed capacity. About 10% of the final energy consumed originated from modern renewables in 2015 (REN21, 2017) against about 2% in 2005 (REN21, 2005). On the one hand, this rate of technological change is high, but on the other hand one can wonder if this pace is high enough to keep the global mean temperature increase below 2°C, or even below 1.5°C, as agreed upon in the Paris Agreement (United Nations, 2015). Therefore, it is of interest to explore current and potential developments in the energy system. In order to gain understanding of the drivers of change, this introductory chapter first goes back in time to the previous energy transition (i.e. the Industrial Revolution). It looks at technological change and the environmental problems accompanied with this technological change. Furthermore, it explores the development in scientific literature when it comes to understanding of environmental problems and it looks at the scientific insights regarding the drivers of change and the means to handle the environmental problems, before arriving at the main aim of this thesis.

1.2 The Industrial Revolution

Two and a half centuries ago, humanity was on the verge of a transition, which we now call the Industrial Revolution. This transition was made possible due to a substantial increase in the supply of energy (Fröling, 2009). Energy consumption was about 20 GJ $\cdot$ capita^{-1} yr^{-1} in 1800; the per capita energy consumption was about three times higher in 2016 and absolute energy consumption has increased twentyfold in this period (Grübler, 2004; IEA, 2016). This tremendous increase in energy consumption was made possible through a shift from flow to stock resources, in other words, a shift from biomass combustion to fossil fuel combustion (Fröling, 2009). Before the Industrial Revolution, the demand for mechanical energy was dependent on manual labour, draft animals, water and windmills alone. Chemical energy for heat and lighting purposes was available in the form of biomass and thus, society was dependent on natural flows of energy (Grübler, 2004). The availability of wood in England, where the Industrial Revolution initially took off, was much smaller than other European countries around 1800, due to high wood demand for material and fuel purposes (Hughes, 2009). This shows that the consumption rate was higher than the natural regeneration rate of biomass. The further development of the steam engine by James Watt in 1765 (Fröling, 2009) and its subsequent patent in 1769 (MacKay, 2008), which can be seen as the starting point of the Industrial Revolution (MacKay, 2008; Fröling, 2009) or energy transition, decreased the demand on wood for fuel purposes by substituting it with coal (Hughes, 2009). Thus, scarcity issues related to biomass were initially solved by shifting the demand for energy to another material system, whilst sustaining growth. Coal consumption and the associated emissions of carbon dioxide (CO_2) increased rapidly from this point forward (MacKay, 2008). Besides that, fossil fuel combustion is associated with other pollutants, such as sulphur oxides (SO_x) and nitrogen oxides (NO_x) (McKinney and Schoch, 2003). The wide availability of fossil energy, used in industrial processes, resulted in growing levels of pollution in abiotic ecosystem compartments such as, air, water and land (Hughes, 2009) in the second half of the nineteenth century. With these growing levels of pollution, the scale of the environmental effects increased over time. Coal is a major contributor to the formation of SO_x, due to the oxidation of sulphur at high temperatures. These substances result in air pollution on a local and regional scale. When reacting with water in the atmosphere, sulphuric acid is formed, which is better known as acid precipitation. This can disperse over hundreds of kilometres increasing the scale of pollution beyond national boundaries. Furthermore, the combustion of coal and liquid transportation fuels results in the formation of NO_x due to oxidation of nitrogen in the air and the fuel when combusted. NO_x, just as SO_x, contributes to acid rain (McKinney and Schoch, 2003), which was first noticed in 1872 (Hughes, 2009). In addition, NO_x contributes to the formation of smog, which is a local environmental problem, initially caused by the combination of smoke and fog. Nowadays, smog refers to secondary photochemical pollution from industrial sources, such as coal-fired power plants and liquid transport fuels (McKinney and Schoch, 2003; Hughes, 2009), where the NO_x reacts with sunlight into the photochemical pollutant ozone (McKinney and Schoch, 2003). These environmental pollutions resulted in human health effects, deterioration of ecosystems and decreasing crop yields (McKinney and Schoch, 2003).

Besides environmental effects from fossil energy consumption, such as acid precipitation and smog, there are emissions of greenhouse gases (GHGs) affecting the mean temperature on a global scale. Arrhenius elaborated on the natural greenhouse effect, caused by the presence of water vapour and CO_2 in the earth's atmosphere in 1896, and calculated that a doubling of CO_2 would lead to a five centigrade temperature increase (Arrhenius, 1896). Arrhenius aimed to explain the coming and going of the Ice Ages and therefore wondered if changes in CO_2 concentrations could have occurred rapidly enough to be the driver for the Ice Ages. Despite this aim, the paper implicitly suggests there is a potential of fossil fuels to contribute to global warming, with the notion that the natural sequestration of CO_2, by weathering of limestone, is in the same range as the CO_2 emissions from coal combustion at that time (Arrhenius, 1896). Concentrations of CO_2 have risen from around 280 ppm before 1800 (Hughes, 2009) and surpassed 408 ppm in 2017 (Kuhns and Shaw, 2018). Current scientific evidence shows that human induced changes to the composition of the atmosphere have resulted in an increase of about 0.6°C compared to pre-industrial times (O'Neill et al., 2017). Global climate change is accompanied with risks, for which global mean temperature change is an often used indicator. Extreme weather events and rising sea levels are rather easy to comprehend as risks forthcoming from temperature change, due to increased evaporation and melting land ice. Other risks, mentioned by O'Neill et al. (2017), such as ocean acidification, deteriorating ecosystems, distribution of impacts and the possibility of large scale singular events (i.e. tipping points) are less straightforward to capture. Still, it is clear that the use of fossil fuels has global consequences that need to be addressed on several levels.

1.3 The need for an energy transition

Mitigation of climate change is on the global agenda, which is visible in the Paris Agreement where 194 countries and the European Union (EU) have expressed the ambition to pursue efforts to remain below a 2°C increase in global mean temperature (United Nations, 2015). Currently, about 170 countries and the EU have ratified the Paris Agreement (United Nations, 2016). Arriving in a state where the net emissions of GHGs are zero, by either using renewable energy, end-of-pipe solutions, such as the underground storage of GHGs, or a combination of both, requires substantial system change which is not a straightforward procedure. The timeframe available to stay below a 2°C increase can be illustrated with the so-called carbon budget. Total emissions of GHGs since the reference period (1861-1880) should remain below 2900 Gt CO_2 including non-CO_2 drivers (IPCC, 2014). The larger part of this budget is already consumed in the last 150 years. According to the IPCC (2014), the remaining budget was 1000 Gt CO_2 in 2011. At existing rates of 38.1 Gt CO_2 in 2011 (IPCC, 2014), a linear decrease to zero emissions should be achieved in exactly 45 years from now. In addition, technology is not the only function that affects the environmental impact. Ehrlich and Holdren (1971), describe the environmental impact as a straightforward linear relation, which is determined by the multipliers of population, and the per capita impact. The latter can be determined by the multiplication of per capita consumption and the impact of the technology used to foresee in this consumption. The United Nations project an increase of 2.2 billion in population up to 9.7 billion in 2050 of which the larger part is expected in Africa and Asia (United Nations, 2017), respectively a developing and transitioning continent. Consumption patterns in these regions can be expected to become more affluent and shift in the direction of consumption patterns in the most developed regions. According to MacKay (2008), per capita GHG emissions in Europe are roughly a factor three higher than Asia and a factor two to four in, respectively North and Sub-Saharan Africa. These simple numbers illustrate that an increase in absolute energy demand can be expected, whilst a decrease in energy related emissions is necessary. So far, increases in energy efficiency and renewable energy production have not been able to decrease the absolute energy consumption and emissions. Hence, the primary energy supply increased to 570 exajoule in 2015 (IEA, 2017) and the annual increment of 3.03 ppm CO_2 (Earth System Research Laboratory, 2018) was at an all-time high in 2015. Therefore, the technological assignment, to mitigate climate change, and realise system change on a global scale in such a short timeframe, is substantial.

Besides climate change, there is another argument on a global scale in favour of system change, namely resource depletion. Hughes (2009), mentions that in England at the start of the Industrial Revolution, forests were being depleted in order to foresee in demand for fuel. These national issues were then resolved by substitution of wood with coal and expansion, by importing resources from colonies (Hughes, 2009). There are limits to expansion as addressed by Malthus (1872) in relation to population growth and the availability of arable land. The same holds for other resources, such as fossil fuels. Recent estimates for the ratio of reserves over production for oil, coal and natural gas are, respectively 50, 153 and 52 years (British Petroleum, 2017). The aforementioned timeframe of 45 years is therefore not only driven by the 2°C climate ambition, but also by the decreasing availability of fossil resources, since further expansion is not an option. The limits related to the use of stock resources were mentioned by Arrhenius in 1920 when he emphasised that coal fields will be exhausted after a certain time. “When this calamity will happen, and the probability of the discovery of substitute sources of energy, are questions of vital importance” (Arrhenius, 1920). The risk related to the dependence on an exhaustible stock resource, was emphasised by Hubbert’s peak theory (Hubbert, 1956). His peak theory argues that production of a resource will follow a bell-shaped curve, or a normal distribution. This means that at a certain point in time, the production levels of a resource will stagnate and subsequently decline. Hubbert did not see this resulting in a calamity, since he expected a lot from nuclear energy as a substitute source of energy. It was not until the publication of Limits to Growth, commissioned by the Club of Rome (Meadows et al., 1972) that environmental issues and resource depletion became more widely recognised as global risks. By recognising the global impacts of fossil energy use related to climate change and resource depletion it became clear that the existing system in which energy and materials were consumed was not sustainable on the long term. In addition, the current consumption of energy and materials is still not sustainable, since it shows a close connection to the business as usual scenario from Limits to Growth (Turner, 2014), resulting in resource shortages, overpopulation and global pollution (Meadows et al., 1972). The Brundtland report “Our Common Future” (Brundtland, 1987) can be regarded as a moment in time after which atmospheric pollution, resulting in global climate change, adjusted the discussion about the design of the energy system and formed the basis for the need for an energy transition.

The focus of environmental problems has historically been on direct effects and specifically on acute (e.g. acid rain and smog) instead of chronic effects (Holdren and Ehrlich, 1974). Meanwhile, the large scale use of fossil fuels has manifested two chronic environmental effects, resource depletion, due to the use of stock resources and climate change, due to the emission of GHGs. Whilst, the acute effects of pollution on a local, regional, national scale and beyond due to the use of fossil fuels still exist, the chronic effects gain more attention. The major shift from flow to stock resources formed the origin of these two environmental externalities, which affect the global environment. The term environmental externality is an economic concept that refers to "[…] uncompensated environmental effects of production and consumption that affect consumer utility and enterprise cost outside the market mechanism" (United Nations, 1997). These environmental externalities became to some extent known in literature more than a century after the start of the Industrial Revolution (Arrhenius, 1896; 1920) and it took roughly another century before the social cost of these environmental externalities became widely recognised as a global risk (Meadows et al., 1972; Brundtland, 1987). In summary, the need for an energy transition is clear. Both chronic effects guarantee the future occurrence of an energy transition, willingly or unwillingly.

1.4 Carbon lock-in and sustainability transitions theory

Again, after two and a half centuries, humanity is on the verge of an energy transition. However, changing the energy system is not a straightforward procedure. In order to understand the inertia of the energy system, one should go back in time and consider the work of Adam Smith, the author of "The Wealth of Nations" in 1784. He can be argued to be the founding father of our modern economic system, driven by increasing returns to scale. Whilst these increasing returns have clearly contributed to the wealth of modern economies, there is a drawback. Arthur (1989) shows that increasing returns can result in a technological lock-in, which is not definitely the optimal alternative and not easily changed. In addition, Unruh (2000) argues that these increasing returns to scale have been the driver for a carbon lock-in of modern economies and that, as a result of this, there are market and policy failures hampering the introduction of renewable energy technology. Hence, the existing fossil energy system is established in a techno-institutional context, where the institutions were adjusted over time to stimulate the increase of the fossil energy system. Nowadays, these institutions hamper the diffusion of renewable energy technology (Unruh, 2000). Besides institutions, there are other factors contributing to this lock-in. Such factors can be, organisational, industrial, societal and technological (Unruh, 2002). The energy transition is a challenge, due to carbon lock-in, since it is comprised of a variety of factors requiring change.

Shifting from fossil to renewable energy can be done by changing the resource use on the consumption or the production side. On the production side, a variety of renewable energy sources is available (e.g. solar, wind, hydro, geothermal or biomass). On the consumption side such renewable energy sources have to foresee in the supply of energy suitable for electric appliances, heating and cooling and transportation. All the available technologies have their own specific characteristics and with that, their own advantages and disadvantages. From a technical and environmental perspective, hydropower is able to respond to fluctuations in demand and supply, but also affects land use. In addition, local geographic circumstances determine the suitability of hydropower (Yüksel, 2010; Ellabban et al., 2014). This is illustrated by the large differences in the share of inland energy consumption of hydropower within the EU. In Austria and Sweden this share is over 10%, whilst the EU average is 1.8% (Eurostat, 2018). Solar energy can contribute to the supply of heat and electricity (Ellabban et al., 2014), but is limited by the amount of solar irradiation at different geographic locations and daily and seasonal cycles.

Besides that, storage of electricity is still technologically challenging. There are multiple promising technologies available for electricity storage, but they are currently not implemented on a large scale (Lund et al., 2015). Just as solar energy, wind energy is free of charge and potentially infinite but it is subject to variation in wind speed, affects land use and has storage issues (Lund et al., 2015). Geothermal energy has an advantage over wind and solar, since it can continuously supply energy. Besides that, it supplies heat instead of electricity, which is a large part of the energy demand in households, almost 80%, (Eurostat, 2017) and industrial processes, about 70%, in the EU (Fleiter et al., 2017). Furthermore, geothermal energy contributes for 0.4% to the EU energy consumption (Eurostat, 2018), meaning that when implemented on a large scale, new supply grids have to be installed at the cost of existing grids.

Biomass as an energy source is argued to be abundant and renewable (Ellabban et al., 2014). In addition, biomass is the only renewable carbon carrier and thus offers complementary opportunities to the current carbon lock-in. It can be combusted in order to produce heat and power and it can be converted with a variety of technologies into liquid or gaseous fuels and building blocks for the chemical industry (McKendry, 2002a; 2002b). Thus, biomass as a primary energy carrier matches with the supply and demand side of the current energy system. The perception of biomass as a renewable resource is visible in the EU's energy policy (European Commission, 2012) and in its renewable energy statistics, which shows that almost two-thirds of the renewable energy was derived from biomass and renewable waste in the EU28 in 2016 (Eurostat, 2018). Biomass is regarded as a flow resource within the bioeconomy strategy (European Commission, 2012). The regeneration rate of biomass is much higher than the regeneration rate of fossil resources, which justifies an approach towards biomass as a flow instead of a stock resource. This legitimates its application as a renewable resource. However, scarcity issues may arise due to high expectations for biomass as a substitute resource for fossil carbon, possibly resulting in an imbalance between supply and demand or resource depletion. Hughes (2009), showed that this was already a reality in England in the first decades of the Industrial Revolution. Biomass should be cascaded based on economic value as presented in figure 1-1 (European Commission, 2012), where the highest value is at the top of the pyramid and the lowest value at the bottom; for the physical quantities the inverse holds. This should result in more efficient use of materials and waste streams. The cascade, however, shows continued linear consumption, by combustion of biobased liquid transport fuels and application of biomass for electricity and heat, which does not overcome possible scarcity issues.

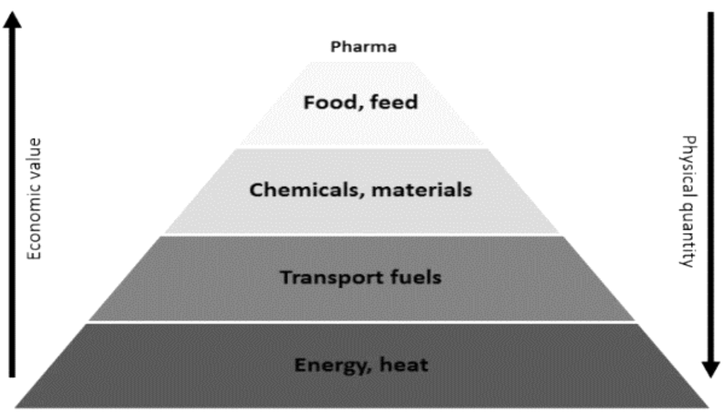

Figure 1-1: Overview of economic cascading of biomass in a bioeconomy (based on Lange et al., 2012).

Global projections on the longer term for the potential of primary biomass have large margins varying from 33 to 1135 EJ · yr^{-1} in 2050 (Hoogwijk et al., 2003). The review by Laugs and Moll (2017) shows that the future projections for biomass based on thirty quantified energy scenarios vary roughly between 120 and 250 EJ · yr^{-1} in 2050. Compared to 48 EJ in 2005 (Heinimö and Junginger, 2009) roughly a two to fivefold increase is expected. This suggests, that at best, biomass can partially foresee in the future energy and material demand for carbon. Substituting fossil with renewable carbon, whilst refraining from system change, is the current trend. Hence, biomass is often applied for electricity, heat, green gas or liquid fuels, which are all complementary to the existing energy system and in the lower part of the biomass cascade (figure 1-1). Complete substitution of fossil carbon with renewable carbon is not obvious given the annually available quantities. In addition, it is questionable whether increasing quantities of biomass for energy can keep up with the absolute increase in energy demand. This can be illustrated with the transport sector in the EU. The total number of passenger vehicles has increased with 4.5% between 2011 and 2015 (ACEA, 2017). The share of biofuels mixed with conventional transportation fuels fluctuated around 5% in the same timeframe (Flach et al., 2017). Biofuels are an institutional solution for carbon lock-in, but currently, the net effect when it comes to mitigating climate change is about zero. Besides this, electrification of private transport is occurring in the EU as an alternative for the use of conventional and biofuels. Despite only 0.15% of the private transport fleet being electric and only representing 1.2% of new sales in 2015, the absolute quantities sold show a strong increase (EEA, 2016). Continuation of this trend, with an increasing scale of application and increased dependency on lithium for batteries, may alleviate pressure on conventional and biofuels and address climate change, but may also be accompanied with scarcity and shifting geographic resource dependency.

Even though environmental effects, such as climate change and depleting resources, are understood for half a century, the share of renewable energy was only 13.2% in the energy mix of the EU28 in 2016 (Eurostat, 2018). When aiming to overcome the factors contributing to carbon lock-in and the inertia of the existing energy system, understanding of the drivers or processes involved in system change is recommended. Gaining understanding of such drivers can be done by looking at previous transitions. Historic analyses of transitions have led to a variety of frameworks related to sustainability transitions theory; the Multi-Level Perspective (MLP) on sustainability transitions and the Technological Innovation System (TIS) are the ones most frequently applied (Walrave and Raven, 2016) to analyse change. The MLP aims to explain the socio-technological dynamics in transition and the TIS aims to explore the dynamics of diffusion of a technological innovation into a system by setting a number of pre-conditions. Reflecting on historic transitions by means of sustainability transition frameworks can contribute to understanding the dynamics of transition and be a starting point to overcome the stage of carbon lock-in.

The previous energy transition, can be considered emergent (Geels, 2011). Beck et al. (1994), argue that when the perception of environmental problems changes from “a problem of the world surrounding us” to an “institutional crisis of industrial society itself”, self-reflection is needed when looking at further technological development. This requirement of a shifting perception of global environmental problems from chronic to acute is in line with Holdren and Ehrlich (1974) and Unruh (2002) who argues that external forces are probably required before action is undertaken. Waiting for the occurrence of external forces or large scale singular events as elaborated by O’Neill et al. (2017) is a substantial risk. The second part of the statement by Beck et al. (1994), addressing self-reflection is, however, already occurring. First, the current energy transition is shaped around the concept of sustainability, where sustainable development is defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Thus, the current energy transition is goal-oriented instead of emergent. Second, sustainability transitions theory analyses the processes involved in system change. When change is not emergent, but goal-oriented with the collective good being regarded as the desired outcome, guidance is required. Geels (2011), argues that the factors that need to be taken into account to analyse and steer sustainable transition are, technology, politics and its resulting policy, economics and culture or norms. This shows that in order to steer change towards the collective good, there is more than a technical and resource issue alone that needs to be resolved; societal aspects, organisational aspects, new norms, new structures and processes and powerful agency of the incumbents, should be taken into account in order to guide the energy transition. Here, it is argued that, whilst environmental problems are generally regarded as "a problem of the world surrounding us" there is reflection on technological development and how the energy transition should be guided. Independent of the perception of environmental problems, the insights from sustainability transitions theory can contribute to the guidance of the energy transition by finding the best strategies, at different stages of the energy transition in order to steer change along the desired pathway.

1.5 European energy policy

Guidance of the energy transition, especially since it is goal-oriented towards sustainability, which can be regarded as a collective good, requires policy. Policy is of importance to guide the energy transition, since it provides the context and direction in which the energy transition takes place. The EU has signed the United Nations Paris Climate Agreement, together with 174 countries (United Nations, 2016). A clear vision on what should happen may therefore be expected from the EU. In 2015, the Energy Union was introduced which aims to provide "secure, sustainable, competitive and affordable energy" (European Commission, 2015a). Competition can be regarded as a precondition for the affordability of energy. Therefore, the main energy policy from the EU revolves, around three objectives, namely security of supply, affordable energy prices and sustainable energy consumption (European Commission, 2015a; 2017a). Keppler, (2007) explains the presence of internal friction within these three objectives with his unsolved triangle of European energy policy (see figure 1-2). Simply optimising the three aspects of this triangle does not work, which can be illustrated with two examples. First, currently low coal prices have a positive effect on security of supply and economic competitiveness, but it has a detrimental effect on the environmental objectives. Second, intermittent renewable power may meet the environmental objective and in some cases result in economic competitiveness, but storage issues still put a burden on security of supply.

Alkemade et al. (2011) explain that there is a conflict between innovation and transition policy by arguing that "[…] policy […] may not only be misaligned but may even conflict as transition policy focuses on stimulating the new and phasing out the old whereas innovation policy often focuses on sustaining the old". Kivimaa and Kern (2016) argue that "[…] policy mixes favourable to sustainability transitions need to involve both policies aiming for the 'creation' of new and for 'destroying' (or withdrawing support for) the old". Therefore, the effect of innovation on the energy transition is unsure due to this internal friction within the European policy objectives. Despite this, innovation plays a key role in the concept of the Energy Union. Hence, the European Commission advocates in its Energy Union communication that a new strategy for research and innovation is required and that an innovation driven transition provides space for economic growth (European Commission, 2015a).

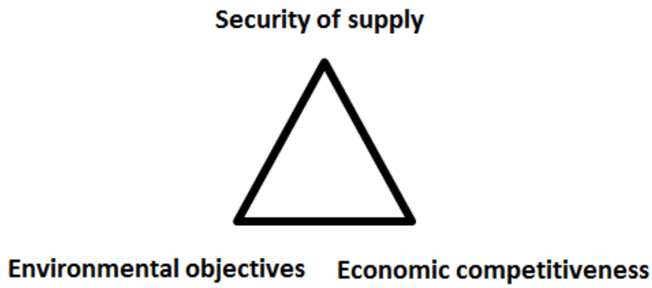

Figure 1-2: The unsolved triangle of European energy policy (based on Keppler, 2007).

The energy transition should lead to structural change of the existing system in order to overcome the challenges of climate change and resource depletion. Therefore, the question is whether the pace at which policy driven innovation manifests itself and introduces change to the incumbent system is enough, to mitigate the global environmental effects of climate change and resource depletion. Or alternatively phrased, is the pace at which policy driven technological innovation manifests itself and introduces change to the incumbent system, enough to prevent a global change of perception, from a chronic to an acute problem, by external forces or large scale singular events?

1.6 Aim and scope of the thesis

The need to change the energy system is clear, climate change and resource depletion. Availability of the required resources to realise this change in the required timeframe is insecure. The perception of climate change as a chronic problem and the need for a goal-oriented approach towards the collective good, do place the incentive for guidance of change on a governmental level. System change is not only a governmental matter when it comes to responsibility, but the EU can take a strong responsibility for the energy transition. The existing strategies imply that the EU is also willing to take such responsibility. However, the future contribution of technological innovations, in line with proposed European strategies, to the energy transition is insecure and therefore worth exploring.

Therefore, the main aim of this thesis is to explore the potential contribution, of some current and possible future technological innovations, to the energy transition.

This resulted in the following overarching research question: to what extent do some current and expected future technological innovations, contribute to the energy transition?

This thesis aims to explore the effect of technological innovation on the energy transition in the context of resource dependency and climate change. As elaborated, there are multiple challenges related to overcoming carbon lock-in. Whether technological innovation is enough to overcome carbon lock-in and address resource dependency and climate change in the required time frame is explored by analysing three technological innovations. It continues with four result chapters and finalises with a general conclusion. Chapter 2 addresses the challenges in the transportation or mobility sector. It explores material scarcity and shifting dependencies in the private transportation sector by means of a chain analysis, where lithium availability for electric vehicle batteries in private transportation was explored, with an emphasis on substitution of lithium in other sectors.

Subsequently, chapter 3 zooms in on the lower part of the biomass cascade in the bioeconomy strategy. This was done by a chain analysis exploring biomass co-combustion in a coal-fired power plant, which is currently a trend in the Netherlands. This is the second technological innovation discussed in this research and it analyses the implications of biomass co-combustion for electricity production by adjustments of existing coal conversion technology, set against the indicators of the Renewable Energy Directive (European Commission, 2009).

When regarding biomass as a potentially scarce resource, deliberate application of biomass is necessary. Biomass gasification technology is a potential future innovation, since the technology can convert biomass to basic gaseous molecules (Speight, 2015). These molecules can be converted to synthetic natural gas, a green gas suitable for injection into the existing natural gas grid. Large scale application of biomass gasification is the third innovation discussed in this research. Chapter 4 is applied to gain insights in the effect of large scale green gas production. It analyses the environmental impact and energy performance of a green gas supply chain when it replaces 1% of the current natural gas consumption in the EU28. In perspective, this 1% corresponds with half of the currently required quantities of natural gas in the Dutch residential sector for the supply of heat.

The Dutch residential sector is largely dependent on low caloric natural gas for the supply of heat. Biomass gasification with green gas production can theoretically play a large role in this sector when shifting to a more sustainable heat supply. However, this is a developing technology; its diffusion into the energy system is subject to a number of factors and its successful contribution to supply heat for the Dutch residential sector within the required timeframe, is unsure. In addition to exploring technological potential, this research focuses on the opportunities and barriers of biomass gasification from a socio-technological point of view to find if the current green gas ambitions are feasible. Thus, chapter 5 is applied to explore a case where the feasibility of the diffusion of biomass gasification for green gas, applied in the Dutch residential sector, is analysed.

Finally, chapter 6 provides the general conclusion and discussion. This chapter is applied to summarise the potentials and limitations of the explored technological innovations to contribute to the energy transition and answer the main research question. Additionally, the final chapter reflects on the results and aims to provide some recommendations for the explored innovations and some general recommendations for the energy transition.

2

Lithium supply and demand dynamics

Lithium availability in the EU27 for battery driven vehicles: The impact of recycling and substitution on the confrontation between supply and demand until 2050.

Abstract
The adverse impacts of climate change are widely recognized as well as the importance of the mitigation of carbon dioxide (CO_2). Battery driven vehicles are expected to have a bright future, since greenhouse gas emissions can be reduced. Lithium-ion (Li-ion) batteries appear to be the most promising, due to their high energy density. Recently, the discussion concerning adequate lithium carbonate (Li_2CO_3) resources is resolved. The current challenge is the needed increase in flow rate of Li_2CO_3 into society to foresee in forecasted demand. This research determines ten factors which influence the availability of Li-ion batteries for the EU27 in the coming decades. They are used in a system dynamics analysis. The results of this research show that undersupply can be expected in the EU27 until 2045 somewhere between 0.5 and 2.8 Mt. Substitution of Li_2CO_3 in other end-use markets and recycling can relieve the strain on Li_2CO_3 supply to some extent. In 2050, 20% of the vehicle fleet in the EU27 can be battery electric vehicles (BEVs). The lack of resources in the EU27 and the geographical distribution of lithium in politically sensitive areas suggest that the shares of lithium available for the EU27 will be less than assumed in this research. The increase in flow rate shows to be the bottle-neck for a transition to (partly) battery driven vehicles in the EU27, at least when Li-ion batteries are used. Focusing on large scale application of BEVs with Li-ion batteries in order to substantially mitigate CO_2 emissions in transport is a futile campaign.

Keywords
Lithium supply, Lithium-ion (Li-ion) battery, Substitution, Battery electric vehicles (BEVs), Plugin hybrid electric vehicles (PHEVs), Security of supply.

Chapter information	
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Salar de Uyuni, Bolivia (2011).

2.1 Introduction

The adverse impacts of climate change are widely recognized as well as the importance of the mitigation of carbon dioxide (CO_2). Besides the adverse environmental impact, the dependence on fossil fuels has resulted in increasing scarcity, which is accompanied with rising energy prices. The electrification of the vehicle fleet can contribute to the mitigation of CO_2, because the application of (partly) electric vehicles reduces greenhouse gas (GHG) emissions when renewable energy sources are used for the production of electricity, or when for example carbon capture and storage is applied. Since transport is responsible for half the global oil consumption (Fulton, 2004), large scale application of battery driven vehicles has potential to mitigate GHG emissions and decrease oil demand. Furthermore, a decreased oil demand and an increase in energy derived from a variety of renewable energy sources, increases security of energy supply. Lithium-ion (Li-ion) batteries have a high energy or power density (Grosjean et al., 2012) compared to other common battery chemistries. Therefore, Li-ion batteries appear to be the most promising for application in battery driven vehicles.

As stated by Gruber et al. (2011), there are significant variations in the estimates for lithium carbonate (Li_2CO_3) resources and reserves. Recently, they resolved the controversy in literature concerning the adequate resources of Li_2CO_3. Long term scenarios until 2100 show that lithium resources are sufficient to fulfil future demand for batteries (Gruber et al., 2011). A select group of countries has direct access to these lithium resources and Europe (i.e. Serbia and Portugal) possesses only 3% of them, whilst it is expected to become one of the largest end-users, which makes Europe import dependent (Gruber et al., 2011; Grosjean et al., 2012). Europe's influence on the supply side is therefore limited. Grosjean et al. (2012) expect Europe to be the greatest victim of the geostrategic bottle-neck concerning the polarised distribution of lithium resources. Despite the sufficiency of resource availability, Gruber et al. (2011) mention the challenge to foresee in the establishment of lithium producing facilities at a rate demanded by the automotive industry. Kushnir and Sandén (2012) also emphasise the possible constraint on an increase of the flow rate of lithium into society.

The bottle-neck for a successful transition to an electrified vehicle fleet with Li-ion batteries seems to be the possible limit on increasing the flow rate of Li_2CO_3 into society, together with the share of the Li_2CO_3 flow available for car batteries, which are both still subject to discussion. The main aim of this research is to analyse the confrontation between supply and demand for Li_2CO_3 in the 27 member states of the European Union (EU27) until 2050 for a penetration scenario of (partly) electric vehicles and draw conclusions about the feasibility of such a scenario.

A system dynamics analysis is commonly used to study the complexity of systems' stocks, flows and feedback loops over time. Such studies are not done so far with regard to the lithium availability for large scale introduction scenarios of battery driven cars.

Such a system dynamics analysis, starts with the identification of the drivers and factors that influence the system. Ten factors can be indicated for the case of lithium availability for large scale introduction scenarios of battery driven cars, namely trends in (1) Li_2CO_3 production, (2) the production trends of battery driven vehicles for the EU27, (3) the lithium requirements per kWh battery capacity, (4) the range of a battery driven vehicle, (5) trends in battery recycling and lithium recovery, (6) the share of Li_2CO_3 available for the EU27, (7) the lifetime of a battery, (8) the share of Li_2CO_3 available for vehicle batteries, (9) trends in other end-use markets of lithium and (10) substitution of lithium in other end-uses. These factors are analysed in order to resolve whether the global lithium resources are enough to fulfil the ambitious targets set out by the

EU. The technological factors in the system are chosen quite optimistic, which should result in an estimate for the lower boundaries in lithium demand belonging to the chosen scenario.

In order to approach these factors a supply forecast curve has been developed. Subsequently, vehicle developments in the EU27 and recycling rates have been analysed. The size of other lithium end-use markets has been estimated and the share of substitutable lithium in these markets has been determined.

This article is organized as follows. First, the further outlining of the research context, this is followed by a description of the developed model and scenarios, the associated results discussing the impact of substitution and recycling and the feasibility of a full electric scenario, a discussion including a sensitivity analysis and a thought experiment addressing the application of plugin hybrid electric vehicles (PHEVs) at the cost of battery electric vehicles (BEVs) and a concluding section which reflects on the constraints concerning lithium supply in the coming decades.

2.2 Research context

The data available from literature on which the model, to estimate Li_2CO_3 demand for the EU27 until 2050, is based on, is elaborated in this chapter. Vehicle development is discussed, combined with the applied forecast for PHEVs and BEVs in two scenarios. The theoretical minimum amount of Li_2CO_3 in a Li-ion battery and recycling rates of Li-ion batteries are subsequently addressed. When referring to the terms resource or reserves the definitions as formulated by the United States Geological Survey (Jaskula, 2009) are applied.

2.2.1 Lithium supply curve

Gruber et al. (2011) estimate the minimum reserve to be 102 Mt. This includes all in-situ Li_2CO_3 resources, such as brines, pegmatite and sedimentary rock. Brines contribute for 66% to the total lithium resource. Only 33% of the estimated lithium reserves are currently in production. When looking at the current Li_2CO_3 production sites, it becomes clear that the current producing pegmatite reserve is in the order of 15% of the total reserve, against 85% from brines. At this moment there is no Li_2CO_3 produced from sedimentary rock (Gruber et al., 2011; Jaskula, 2012).

Kushnir and Sandén (2012) argue that a possible increase in production in the Salar the Atacama (a slat flat) could very well be a limiting factor for incentives to start production elsewhere; starting a new mine can take a decade before production starts, which meanwhile ensures the dependency on brine facilities. This is underlined by Ebensperger et al. (2005) whom argue that Chile possesses the overwhelming share of Li_2CO_3 in the Salar de Atacama. Their government tries to retain its world leadership in Li_2CO_3 production, which should be possible when taking their reserve position and mining culture into account. Therefore, Ebensperger et al. (2005) conclude that even though it is not desirable, the most likely outcome is a continuing status quo in the Chilean world leadership. The geographical concentration of directly available resources and the possible unavailability of a major source of production (e.g. through external interference or unexpected dropping of production) can put a severe strain on the Li_2CO_3 production rate (Kushnir and Sandén, 2012).

Because of the uncertainties in future production two supply curves are developed in order to determine the bandwidth of supply. Rockwood Holdings, Inc. recently issued a press release in which they announced to increase production to 50 kt (rockwoodspecialties.com, 2012). In 2009 the government of Bolivia has begun to build a new brine facility for the production of 30 kt per year (Goonan, 2012). Sociedad Química y Minera de Chile S.A. states in a press release from March 2012 that they aim to maintain their market share of approximately 33% in coming years (sqm.com, 2012). The open-pit pegmatite mining operation at Greenbushes in Australia has the target of doubling their production in 2012 to 110 t of Li_2CO_3 (talisonlithium.com, 2012). The best case (BC) scenario takes such developments into account and therefore assumes an average increase in supply in the order of 8% per year. The business as usual (BAU) scenario assumes an average increase of 6% per year (see figure 2-1).

Table 2-1 provides some absolute numbers as a reference. Growth rates are estimated based on the 2010 production of 125 kt Li_2CO_3 (Kushnir and Sandén, 2012). The first half decade of this century showed an annual growth rate of about 3% in production and consumption until 2005 (Ebensperger et al., 2005). The BC scenario assumes a 45 fold increase, which is theoretically feasible for the Salar de Atacama (Kushnir and Sandén, 2012). We assumed the Li_2CO_3 reserves to be between 75 Mt, which is half of the total Li_2CO_3 resource according to Evans (2008), and 102 Mt (Gruber et al., 2011). The conservative assumption of a 50% recovery rate is more often applied in literature (Tahil, 2008; Yaksic and Tilton, 2009; Gruber et al., 2011); therefore at least 75 Mt can be ascribed as a reserve. The quantity of the lithium end-use markets (Jaskula, 2012) and their expected growth rates (Yaksic and Tilton, 2009) are to a large extent clarified.

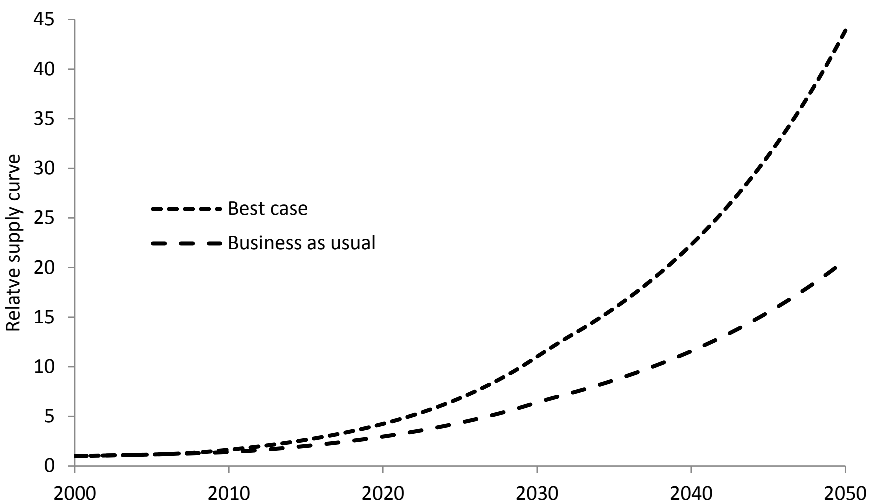

Figure 2-1: The relative supply forecast for Li_2CO_3 until 2050 for the BC and BAU scenario.

Table 2-1: Absolute estimated global supply data for Li_2CO_3 for both scenarios.

Time	Best case (kt)	Business as Usual (kt)
2000	80	80
2020	340	237
2050	3511	1659

The discovery of new resources is not taken into account, since the known reserves are large enough to fulfil the cumulative demand until 2050. Hence, the constraints do not seem to be on the presence of Li_2CO_3, but on the needed increase in flow rate (Gruber et al., 2011; Kushnir and Sandén, 2012). Reserves from producing sites are in the order of 35 Mt, which is about a third of the total reserve. This underlines that the system is not limited by the actual presence of the resource. When looking at the supply curves' growth rates and taking into account that a decade is needed for a new facility to start producing, it becomes clear that 80% to 110% of the estimated supply in 2020 should already be in development in 2010. It seems that this is the case, since there are efforts to increase production rates at existing sites. It is questionable whether currently producing sites can foresee in the 45 fold increase estimated in the supply curve, since Kushnir and Sandén (2012) emphasise that this increase is uncertain for the Salar de Atacama. The possible lag in production can be overhauled by assuming future resource discoveries, by bringing known reserves into production or by producing from marginal sources, such as, seawater with a backstop technology, for example selective capacitive deionization. Confidence in new discoveries and technological innovation can be justified, but actual large scale supply from new resources and backstop technologies is more than a decade away. Therefore, at least in the first decades until 2030 the most should be expected from expansion of existing sites and by bringing known reserves into production.

The United States (US) Li_2CO_3 import cost has roughly been between US $2 and US $4 $\cdot$ kg^{-1} in the past decades (Goonan, 2012). Li_2CO_3 cost per battery in our research are therefore in the order of US $300, which is less than 1% of the total purchasing cost of a BEV. The cost for Li_2CO_3 in a battery are marginal, which suggests that technology improvements on backstop technologies and increased pressure on supply can make these technologies economically viable in the coming decades.

2.2.2 Vehicle development in the EU27

In order to estimate future demand for Li_2CO_3 and to find whether the estimated supply can foresee in this demand a battery driven vehicle penetration rate is estimated together with the amount of lithium needed per kWh.

The average level of car ownership (Eurofound, 2010), combined with population data (Eurostat, 2008), provides the total number of vehicles which is estimated to be 231 million in the EU27 in 2000. Dargay et al. (2007) have estimated future levels of car ownership for 21 countries part of the Organisation for Economic Cooperation and Development, of which 17 are a EU member state. This data is used to estimate the average level of car ownership to be 725 (per 1000 inhabitants) in 2030, which results in a vehicle fleet of 377 million. Dargay et al. (2007) project the global vehicle stock to increase from 800 million in 2002 to over 2000 million in 2030. Therefore the EU27 possesses respectively, 30% in 2000 and 20% of the total vehicle fleet in 2030.

Based on EU scenarios (Reiner et al., 2010) we assume an increase of the annual sales of PHEVs and BEVs from 0% in 2000 to respectively 40% and 12% in 2030 in both scenarios. The actual share of BEVs in the total vehicle fleet is then about 5% against 14% for PHEVs in 2030. The remaining part of the vehicles is assumed to have an internal combustion engine (ICE). Regular hybrid electric vehicles (HEVs) with small battery packs are categorized under ICEs. The larger part of these HEVs do not use lithium containing batteries and are therefore considered as being more efficient ICEs in the context of this research. This scenario is in line with European policy. There is a 10% target for the share of energy from renewable resources in transport in 2020 (European Commission, 2009). This can be met by blending biofuels with conventional transport fuels or by applying battery driven vehicles. The contribution of BEVs and PHEVs in the total vehicle fleet is less than 4% in 2020.

2.2.3 Lithium per battery

The theoretical minimum amount of lithium metal needed to store 1 kWh of chemical energy in a battery is equal to 73 gram. This number results from the multiplication of the theoretical charge density (3.9 Ah · g^{-1}) with the nominal voltage (3.6 V) (Tahil, 2010). In order to produce a Li-ion battery of 1 kWh the theoretical minimum demand for Li_2CO_3 is 0.39 kg. Kushnir and Sandén (2012) and Gruber et al. (2011) use a value of, respectively 160 g and 114 g lithium metal per kWh (i.e. respectively 0.85 and 0.6 kg Li_2CO_3 per kWh). A BEV has a range of 4.4 kilometres (km) with a 1 kWh battery (United States Department of Energy, 2010) or 0.23 kWh · km^{-1}. A range of 200 km (Gruber et al., 2011) with one fully charged battery appears to be on the low side; when comparing with common ICEs the range is a factor 3 to 4 smaller. We therefore assumed that a BEV needs a range of at least 400 km to be of actual interest to end-users, which results in a battery of 92 kWh. For PHEVs a 10 kWh battery is taken.

The BC scenario assumes a linear increase in efficiency of Li_2CO_3 needed per kWh, from 180% to 110% of the theoretical minimum between 2000 and 2050. Thus a battery in the BC scenario needs 696 gram Li_2CO_3 per kWh in 2000 and 426 gram Li_2CO_3 per kWh in 2050. For the BAU scenario the Li_2CO_3 needed per kWh remains 200% for the whole period studied. Thus a battery in the BAU scenario needs 774 gram Li_2CO_3 per kWh. These values are between the estimated values of Kushnir and Sandén (2012) and Gruber et al. (2011) until 2030, after which the increase in efficiency in the BC scenario is assumed to be so high that it will be less than the 0.6 kg according to their estimations.

2.2.4 Recycling of Li-ion batteries

Toxco Inc. has developed patented techniques to recover lithium from wastes or batteries in 1992. They combine the recovery of lithium with the recovery of more expensive materials such as cobalt, aluminium, iron and nickel. Already 98% of the available lithium can be recovered and reprocessed in order to be again available for the production of batteries (Jungst, 1999). This makes clear that it should be feasible and even profitable to recover lithium from waste streams when it is combined with the recovery of other materials. Despite the fact that there seem to be no companies that recover lithium from batteries in the EU27 (Klimbie et al., 2000), the high rate of collection and recycling of more common batteries gives a perspective on what should be possible in the coming decades. Oppenheimer and Abell (2008) expect the recovery of lithium to continue to grow with the increase in production of electric vehicles. Since Toxco Inc. is an example of a company which has made these processes profitable, this research assumes that the absence of large scale lithium recovery companies in the EU27 should not be a limiting factor in the coming decades, when an annually increasing amount of lithium containing waste becomes available for treatment and recovery. More common battery chemistries, such as nickel-cadmium or lead-acid, are collected at a rate in the order of 100% in the Netherlands (Klimbie et al., 2000). This is also a reason to believe that such recycling rates are possible for lithium containing batteries when the facilities for the treatment of these batteries are developed, since the infrastructure for collection is already in place. Therefore, this research assumes a 100% collection rate for Li-ion batteries, of which linearly 3% to 96% is recovered between 2000 and 2030 for the BC scenario, which is in the same range as the recovery rates used by Gruber et al. (2011).

The EU has put into force a directive concerning the recycling of batteries, called directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators (European Commission, 2006). Its primal concern seems to be the achievement of environmental aims. It prohibits producers from placing mercury or cadmium containing batteries on the market.

Besides this, it promotes a high level of recycling and collection of waste batteries. The directive obliges member states to meet collection and recycling targets. In September 2012, 25% should be collected and 50% to 75%, depending on the materials in the battery, should be recovered. In 2016 the collection rate should be up to 45%. The recycling rates are based on average weight of batteries. For Li-ion batteries are no strict regulations, therefore they belong in the 50% recycling category. This research assumes that for the BAU scenario member states will reach the lowest target set by the directive concerning collection and recycling. Both scenarios assume the rate of recycling to increase at the same pace after 2030.

According to the US Environmental Protection Agency, the average annual car mileage is around 12000 miles (EPA, 2010). Considering the lifespan of an average car to be around $2 \cdot 10^5$ miles it will be replaced after 15 to 16 years. This research assumes that the battery and vehicle lifetime are equal, 16 years, and that the existing infrastructure for conventional battery collection can also be used for Li-ion batteries.

2.3 Model and scenarios

This chapter describes the scenarios and the developed model, which are used during this research.

2.3.1 Model description

For the development of the model the dynamic modelling software Stella II 3.0.7© is applied. Figure 2-2 displays a simplified block schedule of the model. The model is driven by the demand for vehicles in the EU27, which is subdivided in ICEs, PHEVs and BEVs. The different types of vehicles are constructed based on the Li_2CO_3 demand in the EU27 including recycling. The block on the outer left describes the global in-situ reserves. The annual global supply is subtracted and a predetermined share is used in the EU27 for the production of PHEVs and BEVs. The amount of Li_2CO_3 produced through recycling is used as an input for new vehicle battery production.

The results from this model are compared with the estimated supply curve, demand from other lithium end-use markets and the possibility of substitution of lithium in these markets. This subsequently determines whether or not there is enough Li_2CO_3 available to produce vehicles according to the estimated market shares for PHEVs and BEVs.

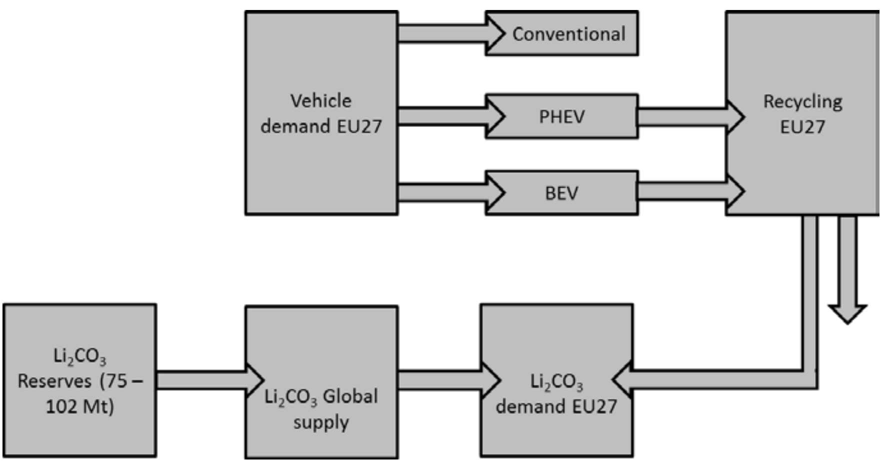

Figure 2-2: Simplified block schedule of the dynamic Stella II 3.0.7© model.

2.3.2 Scenarios

BAU and BC, the studied scenarios, both use the same annual market shares for vehicle development (table 2-2). The BC scenario puts less pressure on the demand than the BAU scenario, since the lithium requirements for batteries are lower. The BC scenario also puts less pressure on the supply because of the assumed higher acceleration of the flow of lithium supply compared to the BAU scenario. The BAU scenario is elaborated to determine the impact of less efficient batteries and recycling rates. The input parameters for both scenarios are summarized in table 2-2. The amount of lithium in a battery is presented as a share of the theoretical minimum. The recycling rates have collection rates for batteries incorporated and the shares for battery driven vehicles refer to annual market shares. This is therefore not the share of (partly) electric vehicles in the total fleet, but the share in the annual sales. The market shares for PHEVs and BEVs continue to grow after 2030 to respectively 75% and 25% of the annual market share in 2050.

The ratios concerning the vehicle penetration rates are derived from Reiner et al. (2010). This scenario is based on the assumption that a globally binding climate convention is closed in 2015. The scenario should call for a reduction of 50% in GHG emissions in 2030; it assumes oil prices in the order of $200 per barrel and a contribution from both utility and manufacturing companies to invest in charging infrastructure. In addition, this is combined with car sharing models and local emission free transport in urban areas. This article addresses the feasibility of such a scenario in the context of the need for a rapidly increasing Li_2CO_3 supply.

Table 2-2: Summarised input parameters for the Best case and Business as Usual scenario.

	Scenario			
	Best case		**Business as Usual**	
	2000	2030	2000	2030
Lithium in battery	180%	138%	200%	200%
Recycling rate	3%	96%	0%	57.5%
BEVs	0%	12%	0%	12%
PHEVs	0%	40%	0%	40%

2.4 Results

Here, the Li_2CO_3 demand for automotive purposes in the EU27 is determined for both scenarios. Figure 2-3 compares this demand with the estimated supply curve (figure 2-1) and shows the share of the annual global Li_2CO_3 supply needed by the EU27 to foresee in their demand for (partly) battery driven vehicles. Demand fulfilled by recycling is taken into account in figure 2-3 which means that the shares displayed are to be derived from virgin material. The decrease in relative demand after 2030 is due to a continuing increase in supply and an increasing contribution of recycling.

Figure 2-3 shows that the BAU scenario demands over 50% of the global supply in a decadal period around 2025 for BEVs and PHEVs, only in the EU27, which seems not feasible when considering other markets both for batteries and other end-uses on a global level. Therefore, this scenario is not taken into account any further. The BC scenario seems more likely with a maximum demand of 22% of the global lithium supply. In order to estimate the share of Li_2CO_3 available for automotive purposes other market developments should be estimated. We used growth rates provided by Yaksic and Tilton (2009) and subsequently the share of Li_2CO_3 which can be substituted was determined. In this way the amount of Li_2CO_3 which can be used for batteries was determined.

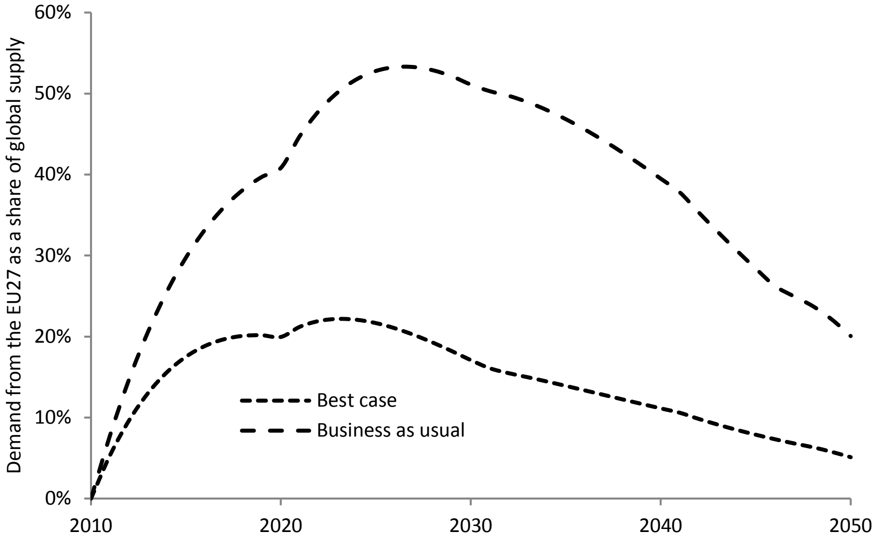

Figure 2-3: The demand from the EU27 as a share of the global production of Li_2CO_3 for automotive purposes between 2010 and 2050 for both the BC and BAU scenario.

2.4.1 Substitution of lithium compounds in other end-use markets and recycling

Jaskula (2012) argues that lithium can be substituted in the production of ceramics, glass, greases and aluminium. Of the 2011 global lithium end-use markets at least 43% (54 kt Li_2CO_3) can be substituted, this decreases to 25% (94 kt Li_2CO_3) in 2030. The demand forecast estimates for different lithium markets from Yaksic and Tilton (2009) are applied in order to calculate the impact of large scale substitution of lithium use in ceramics, glass, greases and aluminium.

The categories for lithium in other end-use markets do not entirely coincide with the categories from Jaskula (2012), therefore the categories pharmaceuticals, continuous casting, polymers and others from Jaskula (2012) are summarized in the category others as provided by Yaksic and Tilton (2009). The primary and secondary battery categories are summarized in batteries from Jaskula (2012). This is justified, since Yaksic and Tilton (2009) estimated demand for automobile batteries apart from primary and secondary batteries. Ceramics and glass, greases and air-treatment are provided by both in similar categories. The production of 125 kt Li_2CO_3 in 2010 is used as a reference for further calculation. For every end-use category, the future demand is calculated by multiplying the market share of the lithium end-use with the 125 kt and the annual change in demand. The amount of lithium needed for other end-use applications than vehicle batteries which cannot be substituted is subtracted from the estimated supply. The substitutable share and the share available for vehicle batteries remain. This research assumes that the amount of annually produced lithium which can be purchased by the EU27, in the form of batteries, vehicles or as high-grade Li_2CO_3, is proportional to the number of vehicles in the global vehicle fleet. In this case a linear decrease in availability is assumed from 30% to 20% between 2000 and 2030 (as explained in section 2.2.2) after which 20% is used until 2050.

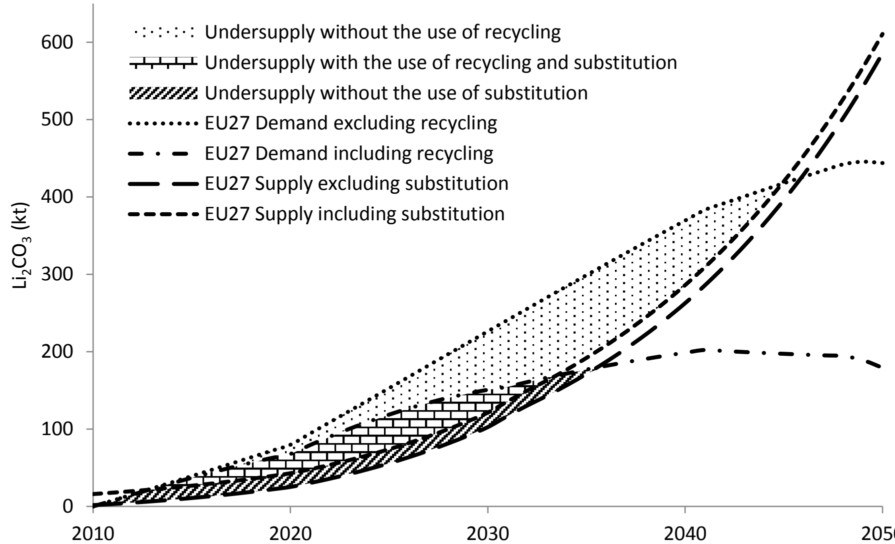

Figure 2-4: The estimated supply and demand for virgin Li_2CO_3 in the EU27 for the BC scenario and the resulting undersupply in the coming decades[1].

Figure 2-4 shows that the BC scenario results in undersupply despite the contribution of recycling and substitution. When substitution and recycling are both applied the supply for vehicle batteries increases and the demand decreases causing the cumulative undersupply to be 0.54 Mt between 2013 and 2033. This undersupply number corresponds with 30 million BEVs that could not be produced (about 15% of the BEVs target for 2030). When there is no Li_2CO_3 available through substitution the undersupply increases to 0.95 Mt until 2035. In this case about 25% of the 2035 BEVs target could not be produced. These numbers show that the assumed application of substitution decreases the lithium undersupply substantially in the first decades. When recycling and substitution are both left out the undersupply amounts to 2.8 Mt between 2011 and 2045. When substitutable end-uses were taken into account the undersupply in this period declines with 0.7 Mt. Figure 2-5 shows that substitution is very important until 2020 to enable the expansion of the BEV fleet in the EU. The impact of substitution in a transition phase is crucial, when recycling is in its infancy, since it strongly decreases the quantity of the undersupply. On the long run the role of recycling is the most important one.

Kushnir and Sandén (2012) conclude that other lithium applications play a role on the margin but do not affect the viability to produce batteries. Our results show that substitution is required in order to decrease the size of the foreseen undersupply after 2013. We agree with Kushnir and Sandén (2012) that the dispersion of lithium in other products is marginal on the longer term (their scenarios end in 2100). However, in a transition phase in which the demand for batteries

[1] The demand excluding recycling assumes that lithium is not recycled, which results in an increased demand for virgin material. Demand including recycling shows a reduction in demand for virgin lithium, due to the application of recycling. Supply including substitution increases the availability for vehicle batteries at the cost of other end-uses. Supply excluding substitution shows the estimated supply in a situation where substitution is not applied. This means that other end-uses demand lithium as well, resulting in a decreased availability for automotive batteries.

is increasing rapidly, substitution can at least relieve the strain on an increased Li_2CO_3 demand to some extent, since the initial impact of recycling is too small to fulfil the hiatus between supply and demand. Therefore, the undersupply of lithium results in the postponement of large scale adoption of electrically chargeable vehicles in society. This shows that the viability of Li-ion batteries in the EU27 is at least partially dependent on substitution. Taking the cumulative size of lithium applications in 2100 (Kushnir and Sandén, 2012) besides batteries, is an approach which appears to be too general, to use as a determinant for the whole century when considering its possible contribution.

Demand for the BC scenario stabilizes after 2040 (figure 2-4) due to an increase in the absolute contribution of recycling and the assumed increase in efficiency of batteries. Between 2013 and 2035 undersupply results in a strain on the availability of Li_2CO_3 especially in the EU27, which has practically no in-situ resources and high ambitions.

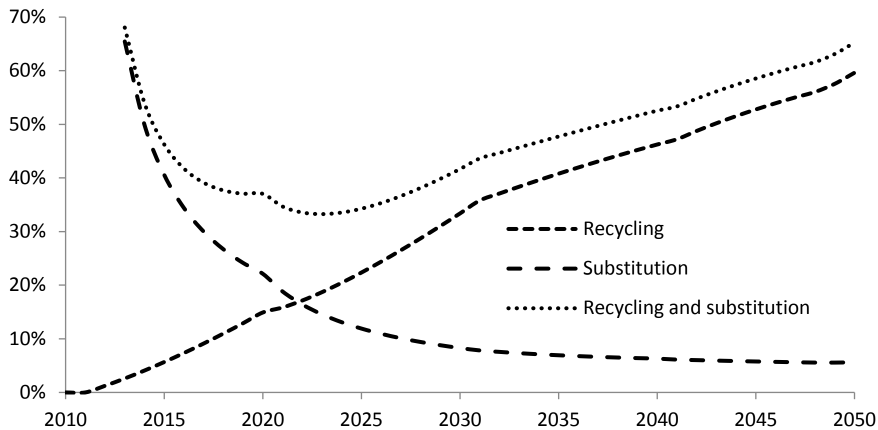

Figure 2-5: The contribution of recycling and substitution (and their combined contribution) to the total demand in the EU27 for Li_2CO_3 in PHEVs and BEVs between 2010 and 2050.

In order to fulfil the demand from the EU27 when assuming that the available share of Li_2CO_3 supply (30% to 20%) is realistic, the BC supply curve has to be adjusted. The 45 fold increase in supply (between 2000 and 2050; see figure 2-1) results in a shortage of 0.54 Mt. In order to fill this gap the annual supply for the EU27 should be on average 36% higher than the estimated availability between 2013 and 2033. Oversupply is visible until 2013 (figure 2-4), which is marginal. If these data for supply and demand were further interpolated into the past, the model shows oversupply for the first 12 years from 2000 forward. This means that an excess of lithium could have been saved by the EU27 in order to foresee to some extent in future undersupply. There seems to be no reason to assume that this is the actual case.

2.4.2 Full electric scenario

In order to determine the size of a full electric vehicle fleet, large scale introduction of BEVs in the EU27 is estimated based on the supply curve for the BC scenario (figure 2-1). With the estimated supply the total amount of BEVs in 2050 can be in the order of 95 million. Full adoption of BEVs is therefore limited, since this scenario results in a share of 20% of BEVs in the European vehicle fleet in 2050.

2.5 Discussion

Most assumptions done in this research are quite optimistic. They concern: high recycling rates, substitution, an average to low lithium content per kWh, long battery lifetime, a rather high share of the lithium supply available for the EU27, a high rate of expansion of existing facilities and development of new facilities. Less optimistic is the assumed high range per BEV. Besides this the battery driven vehicle development scenario seems rather high. However, the applied vehicle scenario results in less than 4% of the vehicle fleet having a battery in 2020 (without taking its feasibility into account concerning undersupply). The EU directive on the promotion of energy from renewable sources (European Commission, 2009) targets on a share of energy of 10% from renewable sources in transport in 2020. When taking into account that PHEVs, despite their batteries still consume fossil fuels and that BEVs might not have tailpipe emissions, but they may still be dependent on electricity with a fossil origin, a lot should be expected from biofuels in order to meet such ambitious targets.

When re-considering the minor fraction of the global Li_2CO_3 resource within the EU27's territory, the assumption that the amount of lithium to be acquired by the EU27 is proportional to the amount of vehicles in the global vehicle fleet, is probably on the high side.

The estimated supply curve uses average increase rates of 6% $\cdot$ yr^{-1} (BAU) and 8% $\cdot$ yr^{-1} (BC). This means that production respectively doubles every, 12 and 9 years. Both are substantial, but still result in undersupply for the EU27. When a decade is needed for a new facility to start producing, this means that 80% to 110% of the estimated supply in 2020 should already be in development in 2010. This means that in 2010 the production of at least 100-138 kt of Li_2CO_3 should be in development. It seems that this may not be the case since Chilean production is expanded to maintain its market share (sqm.com, 2012) and therefore its status quo (Ebensperger et al., 2005) and Bolivian development of the Salar de Uyuni is slower than expected due to the refusal of foreign assistance (The Guardian, 2011). The pegmatite mining operation in Greenbushes however has shown increased production of 55 t of Li_2CO_3 in the last year. This research shows that only 40% of the reserves that are currently in production are needed to fulfil the global demand until 2050. The rate of expansion of producing facilities is therefore the determining driver, since they can respond the fastest to changing demand. When expansion cannot keep up with increased demand, known reserves should be brought in production, since the technology is already available. The large scale application of a backstop technology to produce from marginal sources would take more than a decade. This suggests that when a backstop technology is ready for production the undersupply problem in the EU27 is almost gone, since supply is expected to be larger than demand after 2035. Prices might decrease when this is the case, which could make this backstop technology unfeasible within years.

Our research assumes that when competition occurs between different markets for Li_2CO_3 the automotive sector has the advantage over other applications and, therefore, substitution of lithium compounds will occur where possible. However, even when large scale substitution is applied, the amount of Li_2CO_3 demanded by the EU27 is disproportionally high, when compared to the global size of the Li_2CO_3 market. What becomes clear is that the strain which is put on Li_2CO_3 supply is larger than the results of this research show, since it is rather improbable that other Li_2CO_3 consuming markets can or will switch to other materials in a timeframe of one decade. As further elaborated in the thought experiment, the application of PHEVs at the expense of BEVs during a transitioning period in which Li_2CO_3 supply can increase, might have significant advantages.

2.5.1 Sensitivity analysis

The high rates for recycling should be feasible, since the infrastructure for the collection of vehicle batteries is already in place. Technology is also available and it is economically feasible to recover lithium from batteries when combined with the recovery of other materials. However, the EU already admitted in 2011 that only a couple of countries will reach the 2016 target of 45% collection for waste batteries (euractiv.com, 2011). This shows that recycling rates as formulated in the BAU scenario are not met, let alone the rates estimated for the BC scenario. The assumption for the lifetime of a battery of 16 years is optimistic. Therefore, a sensitivity analysis is applied to estimate the impact of a battery lifetime of 8 years. The sensitivity analysis shows that a doubling of the amount of Li_2CO_3 per vehicle when assuming a battery lifetime in the order of 8 years will not distinctly increase the strain on virgin Li_2CO_3 production. The amount of lithium released earlier for recycling due to an assumed shorter battery lifetime is marginal. The strain is put on increased demand from recycling, since the amount of lithium that needs to be supplied from recycling is a factor 1.8 higher compared to a 16 year battery lifetime. The lack of lithium recovering facilities in the EU27 and the collection targets that are not met so far, suggest it will be a challenge to process such quantities. When 8 years is taken as the lifetime of a battery the shortage decreases from 0.54 Mt to 0.33 Mt. The cumulative demand for virgin material until 2050 also decreases with a little over 3% compared to a 16 year battery lifetime. This is also reflected in the amount of (partly) electric vehicles which are reduced with almost 4%.

The assumed high range (92 kWh for 400 km) for BEVs can be decreased, resulting in a smaller demand for Li_2CO_3 per vehicle. It is unlikely that this will have a significant impact. Hence, when taking a less optimistic battery lifetime and taking halve the assumed range, the results will differ only slightly due to increased, but marginal, availability of Li_2CO_3 from recycling in the first decade of the studied period. In order to estimate the sensitivity of the system to the vehicle range, the impact of a smaller range for two scenarios (a 40 and a 60 kWh battery) is taken into account. A 60 kWh battery, which needs on average 34 kg of Li_2CO_3, is in between the values of Kushnir and Sandén (2012) and Gruber et al. (2011) and still results in undersupply. A 40 kWh battery does not result in undersupply. The last example is highly dependent on whether the collection and recycling rates are attained and if a decreased range is acceptable for the average consumer. The quantity of collection and recycling on the long term seems to be the most crucial factor in Li_2CO_3 supply. Furthermore, the available share of the supply for the EU27, the needed rate of expansion and new reserves being brought in production are of importance in order to foresee in demand.

The optimistic technological assumptions done in this article may probably lead to an underestimation of the pressure on lithium availability (rather efficient recycling rates, an average to low lithium demand per kWh compared to other articles (Gruber et al., 2011; Kushnir and Sandén, 2012), a high share of supply available for the EU27 and a 45 fold increase in production). The results (notwithstanding these optimistic assumptions) demonstrate that the feasibility of the elaborated scenarios appears to be small. A transition to (partly) electric vehicles with a lithium based battery chemistry is therefore not to happen by default.

2.5.2 Thought experiment

The full electric scenario results in 20% BEVs in the European vehicle fleet, against 180% if these vehicles were to be PHEVs (based on battery mass BEVs : PHEVs as 9 : 1). This shows that when a shift in the direction of PHEVs is introduced at the expense of BEVs and ICEs the outlined demand for Li_2CO_3 will approximately halve (80 / 180 = 4 / 9). In times of undersupply one can choose to produce one BEV or (36.5 kg / 4.1 kg; battery requirements in 2050) nine PHEVs consuming the same amount of Li_2CO_3. With an assumed range of 44 km a PHEV is more suitable for commuting distances, since a BEV carries nine times more mass in its battery, whilst only a small part of the battery capacity is used on relatively short commuting distances. This excess of mass reduces the efficiency of a BEV on short distances when compared to a PHEV. In terms of gasoline use nine PHEVs (2.5 litres (l) $\cdot$ 100 km^{-1}) are also more efficient compared to one BEV (0 l $\cdot$ 100 km^{-1}) and eight ICEs (5 l $\cdot$ 100 km^{-1}). When Li_2CO_3 is scarce a shift in the direction of PHEVs at the cost of BEVs and ICEs saves almost 2 l $\cdot$ 100 km^{-1} $\cdot$ $vehicle^{-1}$, which is advantageous for the environment and the average consumer.

2.6 Conclusion

The confrontation between supply and demand for Li_2CO_3 in the coming decades has been studied with a system dynamics analysis. The results show that the share of lithium to be available for batteries on a global scale is significant; the share available for the EU27 is not. Obtaining approximately one-fifth at some stage in time is necessary, but not probable when the optimistic natures of several model assumptions done during this research are taken into account.

The best case scenario estimates a 45 fold increase in Li_2CO_3 supply in 50 years. As shown this ultimately results in an excess in supply (figure 2-4). The coming decades, however, present a distinct undersupply even though an average of 8% increase in production per year is assumed, which is similar to a decadal doubling of the production. Increases in production are stemmed by the fact that these are largely brine dependent. Hence, putting a new facility into production can take a decade. Undersupply is a serious risk in the coming decades. A faster increase in the Li_2CO_3 flow rate than estimated in the BC scenario seems improbable. Besides this, a globally binding climate convention cannot count on a significant reduction in GHG emissions based on the large scale adoption of Li-ion battery driven vehicles.

The impact of recycling is small in the first decades, due to rapid increases in demand and a relatively small waste stream available for recycling. On the longer term the impact of recycling increases. When substitution is applied on a large scale, this could compensate for recycling and alleviate the strain on the undersupply in the EU27. If the supply curve is sound, 20% of the European vehicle fleet can be BEVs in 2050. Instead of 20% BEVs, a 100% PHEV adoption scenario is also feasible requiring less Li_2CO_3 and only 63% of the gasoline demand. This results in postponing the timeframe of undersupply, which suggests that the optimal adoption of BEVs should be gradual, since rapid large scale application of BEVs is not feasible. Therefore, the large scale adoption of PHEVs in a transitioning phase, until Li_2CO_3 is produced on a large scale (at least 45 times the 2000 production rate), would decrease the strain on the production in the coming decades and would also decrease the gasoline demand. This can be followed by large scale adoption of BEVs, but this will require some long term coordination to prevent for undersupply.

When transitioning to an electrified vehicle fleet, the aim should be to not become dependent on another single material. The lack of resources in the EU27 and the geographical distribution of lithium in politically sensitive areas, suggest that the shares of lithium available for the EU27 in the coming decades will be lower than the assumed shares in this research. Combined with the optimistic technological assumptions done in this research, it shows that the flow rate of lithium into society and, specifically the increase in flow rate, is the bottle-neck for a transition to (partly) battery driven vehicles in the EU27, at least when Li-ion batteries are used. Focusing on large scale application of BEVs with Li-ion batteries in order to substantially mitigate CO_2

emissions in transport is a futile campaign and will result in a shift from energy to material dependency at least on a European scale.

3

Biomass co-combustion

Renew, reduce or become more efficient? The climate contribution of biomass co-combustion in a coal-fired power plant.

Abstract

Within this paper, biomass supply chains, with different shares of biomass co-combustion in coal-fired power plants, are analysed on energy efficiency, energy consumption, renewable energy production, and greenhouse gas emissions and compared with the performance of a 100% coal supply chain scenario, for a Dutch situation. The 60% biomass co-combustion supply chain scenarios show possibilities to reduce emissions up to 48%. The low co-combustion levels are effective to reduce greenhouse gas (GHG) emissions, but the margins are small. Currently, co-combustion of pellets is the norm. Co-combustion of combined torrefaction and pelleting shows the best results, but is also the most speculative.

The indicators from the Renewable Energy Directive cannot be aligned. When biomass is regarded as scarce, co-combustion of small shares or no co-combustion is the best option from an energy perspective. When biomass is regarded as abundant, co-combustion of large shares is the best option from a GHG reduction perspective.

Keywords

Biomass, Bio-energy, Co-combustion, Supply chain analysis, Pulverised coal power plant.

Chapter information	
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3.1 Introduction

During the last hundred years, pulverised coal combustion has been widely applied for electricity generation (Barnes, 2015). More recent, deregulation of the European power sector (Barnes, 2015), low coal prices and a plethora of inexpensive emission certificates have increased the lock-in effects of pulverised coal firing in the European Union (EU). Currently, technological innovation is applied as a means to decrease the environmental impact of coal combustion, by increasing the boiler efficiency, co-combustion with biomass or carbon capture and storage (Barnes, 2015).

The Renewable Energy Directive (RED) (European Commission, 2009), as constituted by the European Commission, emerged from increasing awareness about climate change. Hence, the focus is on the reduction of greenhouse gas (GHG) emissions, by using indicators as: increased use of renewable energy sources, energy saving and more efficient use of energy. Biomass has the largest contribution to renewable energy production in the EU; almost two-thirds of the primary production of renewable energy originates from biomass (European Commission, 2014a). Despite criticism on the actual sustainability of biomass for energetic purposes (Schoots and Hammingh, 2015; Katan et al., 2015) biomass is often co-combusted in coal-fired power plants in the Netherlands. Figure 3-1 shows the quantity of biomass co-combusted in the Netherlands from 1995 until 2012. The annual co-combusted biomass quantities after 2005, were directly related to the Dutch subsidy structures (CBS, 2013). During the last decade a tenfold increase in coal exports from the United States (US) to the Netherlands has taken place, up to 230 PJ in 2015. In the same period, the domestic consumption of coal in the Netherlands for electricity generating purposes increased with approximately 60% up to 400 PJ in 2015. Pellet exports from the US to the EU28 increased with a factor nine since 2009 up to 81 PJ in 2015. The amount of imported pellets was equal to the domestic consumption in 2011 in the Netherlands. Assuming that the imports are evenly distributed over the domestic consumption, then about 40% of the consumed pellets in the Netherlands originated from the US. This corresponds to roughly 7 PJ, which is 25% of the co-combusted pellets in the Netherlands. The Dutch Energy Agreement for sustainable growth (SER, 2013) has put a maximum on biomass co-combustion of 25 PJ in 2020. This maximum underlines that the debate regarding the environmental sustainability and optimal application of biomass is still ongoing.

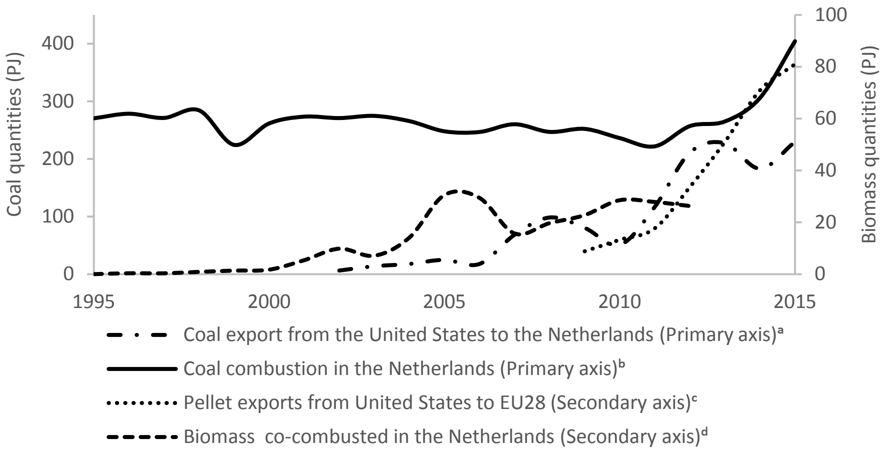

Figure 3-1: Coal exports from the United States to the Netherlands (PJ), coal quantities combusted for electricity production (PJ), pellet exports from the United States to the EU28 (PJ) and co-combusted biomass in the Netherlands (PJ).
a EIA (2016) b CBS (2016a) c FAO (n.d.); Goetzl (2015) d CBS (2016b).

Biomass is a rather dispersed resource (Batidzirai et al., 2013) and generally available in regions with low energy and material demand. This low regional demand results in the need for transport to more material and energy intensive regions. The larger part of the co-combusted biomass in the Netherlands originates from North America (Goh and Junginger, 2013). Giuntoli et al. (2015) showed that low energy densities of biomass result in lower transport efficiencies compared to coal. The logistic disadvantages of biomass can be reduced by applying pretreatment to increase the energy density ($MJ \cdot kg^{-1}$).

When biomass is applied for co-combustion, a supply system complementary to that of coal, has to be designed. However, the impact of the biomass supply chain on the total system performance is often neglected. This is in line with Iakovou et al. (2010) whom state that little research focuses on supply chain issues, whilst taking the whole supply chain into account. Lin et al. (2016) showed that long distance transportation of wood pellets is economically feasible, just as Uslu et al. (2008) showed that biomass transportation could be economically and energetically feasible under certain conditions. However, the actual net quantities of renewable electricity from biomass co-combustion and the related GHG emissions of long distance supply chains are still unsure, since conversion is not taken into account by Uslu et al. (2008) and Lin et al. (2016) only focus on the economic aspects of biomass supply, which at least in the Netherlands has a strong relation with subsidy structures (CBS, 2013).

Therefore, within this article a chain analysis with a variety of biomass supply chain scenarios, including different pretreatment technologies and different co-combustion levels, was performed. The aim of this analysis is to determine the effectivity of different pretreatment technologies, different levels of biomass co-combustion and conversion on the RED indicators, GHG emissions, the energy efficiency, energy consumption and renewable energy production, when the whole supply system is taken into account. Currently, co-combustion of pellets is the norm in the Netherlands. This research studies the effect of co-combustion with different shares of poplar wood chips, torrefied wood chips, pellets and combined torrefaction and pelleting (TOP). The analysis indicates whether renewable energy from biomass co-combustion results in energy saving, increased energy efficiency and finally a reduction in GHG emissions compared to the combustion of coal.

This paper continues with a methodology section describing the qualitative and quantitative aspects of the supply chains. Subsequently, the supply chain scenarios are discussed after, which the results are presented. Furthermore, a discussion section, finalised with a sensitivity analysis, and a general conclusion are presented.

3.2 Methodology and system components

There are two separate upstream supply systems, which merge at the midstream conversion stage (figure 3-2). Coal is mined, transported to a harbour and subsequently transported overseas to the port of Rotterdam in the Netherlands. Poplar is produced, harvested, chipped and dried (up to 20% moisture on a wet basis) on the production site, before the wood chips are transported to a harbour. At the harbour, no further pretreatment, or torrefaction, or pelleting or TOP is applied. Subsequently, the biomass is transported overseas with a Supramax bulk carrier (in line with Giuntoli et al. (2015)) and grinded together with coal at the coal-fired power plant. The coal and biomass are co-combusted on the Maasvlakte where the GDF Maasvlakte pulverized coal-fired power plant is located. This power plant is theoretically able to co-combust up to 60% biomass (Warringa et al., 2016). Figure 3-2 gives an overview of the system boundaries of this research and the design of the supply chain scenarios, which are further elaborated upon in figure 3-3. The midstream part of the biomass supply chain is equal to the coal supply chain, where both feedstocks are grinded and combusted for electric power production. In the following, the individual steps in the supply chains are discussed. This section further elaborates on the calculation of the energy use in transport, the conversion efficiency, the calculation of the share of renewable electricity produced, the 12 supply chain scenarios, and the coal supply chain reference scenario.

For ease of comparison, 1 $MJ_{electric}$ output was taken as the functional unit for all supply chain scenarios. This results in demand driven supply chain scenarios. Hence, the calculated conversion efficiency and the energy content of the pretreated biomass determine the required quantities of biomass.

3.2.1 Coal mining

The first step in coal supply is mining of the resource. Ditsele and Awuah-Offei (2012) provide a life cycle analysis of the impact of modern surface coal mining facilities in the US. The data from this paper are suitable for this analysis, since it provides an overview of the distribution of energy use and emissions of different coal mining situations and it focuses on bituminous coal, which is suitable for conversion in a pulverised coal-fired power plant. The bituminous coal is suitable for grinding further down the supply chain. The coal in the analysed supply chains originates from the US and is suitable for conversion to electricity in the Netherlands. Figure 3-1 shows that coal import from the US to the Netherlands is a recent and increasing trend. The data from Ditsele and Awuah-Offei (2012) is cradle-to-gate data, where the gate is the mine gate. It therefore represents the first block in figure 3-2 (i.e. coal mining). Energy use and GHG emissions of coal mining are presented in table 3-1.

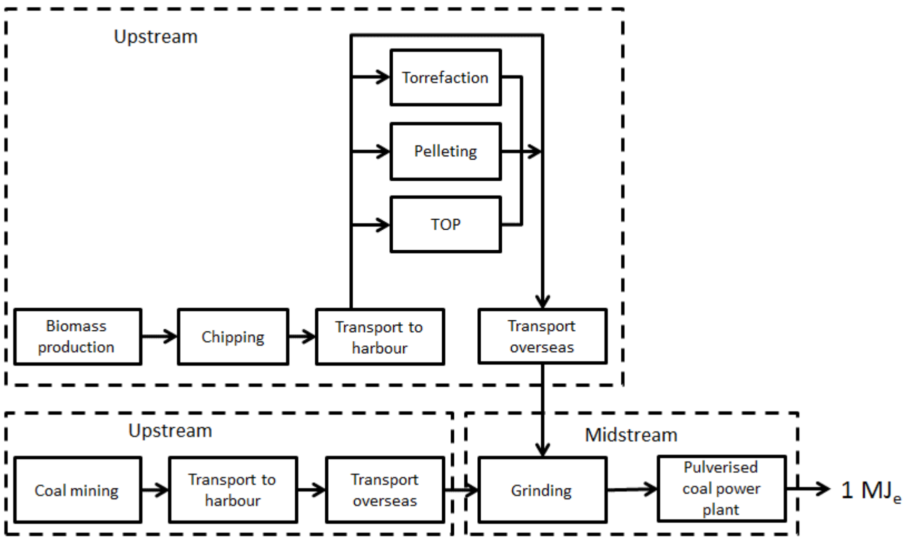

Figure 3-2: Overview of the system boundaries of the analysed supply system for biomass and coal.

3.2.2 Biomass production

For comparability with the reference scenario the biomass production system is located in the US, which is in line with Goh and Junginger (2013). As underlined by figure 3-1 and elaborated upon in the introduction, the amount of co-combusted pellets in the Netherlands, originating from the US, is about 25% of the total. Therefore, the same transport logistics can be applied. The intensive production system for woody lignocellulosic biomass is applied (Miedema et al., 2016). These systems were originally developed for European production sites (Nonhebel, 2002). For the purpose of this research they are suitable, since biomass yields, inputs and energy densities of the biomass are in the same range. The intensive woody lignocellulosic biomass production system includes ploughing and preparation, crop protection, fertiliser application (nitrogen), harvesting, forwarding biomass to the roadside, chipping and loading of the biomass on a truck. Combined data for the energy use and GHG emissions of biomass and coal production are presented in table 3-1.

Table 3-1: Energy consumption and GHG emissions of coal mining and biomass production (data taken from Ditsele and Awuah-Offei (2012) and Miedema et al. (2016)).

Fuel		Low	Average	High	Unit
Coal	Energy consumption	97	124	181	$MJ \cdot t^{-1}$ coal
	GHG emissions	38	62	92	kg CO_2 eq. $\cdot t^{-1}$ coal
Biomass	Energy consumption		656		$MJ \cdot t^{-1}$ biomass
	GHG emissions		65		kg CO_2 eq. $\cdot t^{-1}$ biomass

3.2.3 Biomass and coal pretreatment

This paper analyses three pretreatment technologies for biomass, namely torrefaction, pelletisation and TOP. Transporting biomass in the form of pellets from the US is the norm. The transport of pellets is compared with the transport of wood chips, torrefied wood chips and TOP in order to find whether one type of pretreatment is energetically and environmentally advantageous, compared to pellet transport and co-combustion. In these assumed cases, the production of wood chips, torrefied wood chips, pellets and TOP is taking place in the US, before actual overseas transport. Besides that, grinding or pulverisation of coal and biomass is taken into account at the coal-fired power plant in the Netherlands.

Pellets

Pelletisation is a proven technology, since 650 pelletisation plants produced roughly 10 Mt of pellets in Europe in 2009 (Sikkema et al., 2013). Pelleting or densification is applied to increase the bulk (kg m^{-3}) (Mani, 2005) and energy density of biomass for more efficient transport. For a more extensive overview of the pelleting technology this paper refers to Mani (2005) and Uslu et al. (2008). The applied data for pelleting is presented in table 3-2.

Torrefied wood chips

Torrefaction was not yet a commercially feasible technology in 2011 (Biofuelsdigest, 2011). This is underlined by Koppejan et al. (2012), whom identified over 40 torrefaction initiatives aiming to prove the economic and technological viability of the technology. The diffusion of torrefaction took off in this period and at the end of 2012 a number of torrefaction plants was commissioning, but not yet producing commercial volumes (Deutmeyer et al., 2012). Currently, 65 companies are working on torrefied biomass on a global level (Energiepodium, 2015). Torrefaction is a thermal process with temperatures ranging between 200 and 300 ˚C. The advantages of torrefied wood chips with respect to untreated biomass are, a hydrophobic nature, due to loss of hydroxyl groups (Tumuluru et al., 2011), and the absence of biological activity, which makes storage in an ambient atmosphere possible. Torrefied wood has a more constant product composition, which makes the subsequent conversion process easier to control. The applied data for torrefied wood chips are presented in table 3-2.

Combined Torrefaction and Pelleting (TOP)

There is not yet a substantial market for TOP, but it could become a successor of pelletisation and torrefaction, due to high energy efficiency (Bergman, 2005) and due to the fact that this product has the combined advantages of pelletisation and torrefaction. Therefore, it shows an increase in bulk and energy density. It has a hydrophobic nature and requires less energy for grinding, when compared to pellets or chipped biomass. Prior to size reduction and densification of biomass in the pelleting process, the biomass is torrefied, after which densification is applied. Because of similarities in both the torrefaction and pelleting process, both processes can be combined efficiently (Bergman, 2005). The applied data for TOP is presented in table 3-2.

Grinding

Before the feedstock can be fed to the burners of the power plant, it is grinded or pulverised. Grinding results in a constant particle size (Tumuluru et al., 2011), which makes it possible to co-combust biomass with coal. The energy requirement for grinding of raw biomass is higher than the requirement for grinding of coal (Batidzirai et al., 2013; Tumuluru et al., 2011). Torrefaction, may increase the grindability (Tumuluru et al., 2011), which makes it suitable for co-combustion in a pulverised coal-fired power plant (Bergman et al., 2005; Arias et al., 2008). Therefore, pretreatment of biomass can be an option to increase the grindability of biomass in order to reduce the effects on boiler deterioration and maintain high conversion efficiency.

The energy consumption of the applied biomass pretreatment technologies are taken from literature and presented in table 3-2. Aebiom (2008) states that passive drying is possible up to 20% on a wet basis. Seasoning or drying is therefore done passively, by storing poplar wood chips under cover; the energy requirements for storage are not taken into account. Wood chipping is executed with a diesel driven engine (vande Walle et al., 2007); for diesel a value of 74.1 g CO_2 eq. $\cdot$ MJ^{-1} (Penman et al., 2006) is applied. Torrefaction, pelleting and TOP are based on natural gas. For natural gas a value of 56.1 g CO_2 eq. $\cdot$ MJ^{-1} (Penman et al., 2006; Quaschning, 2013) is applied. For torrefaction and TOP losses in energy content of the biomass fuel are included and assumed to be equal (i.e. 10% of the energy content). Hence, during torrefaction about 10% of the energy content of the biomass is applied for the torrefaction process (Bergman et al., 2005). However, the fossil energy inputs differ for torrefaction and TOP (table 3-2). The energy consumption for torrefaction and TOP are the nominal values provided by Batidzirai et al. (2013). The data for torrefaction are taken from Batidzirai et al. (2013) and are in the same range as data provided by Repellin et al. (2010). Tumuluru et al. (2011) argue that grinding energy of wood chips can be decreased with 70% to 90% when torrefaction is applied. Based on the available data for torrefaction the energy consumption for grinding of wood chips was estimated. This paper assumes that grinding energy of torrefied woodchips is 10%, 20% and 30% of the energy required for grinding of chipped wood for respectively the low, average and high case. TOP has the most coal like properties and is therefore assumed to be the closest to coal. Grinding energy for pellets is assumed to be between torrefied wood chips and regular wood chips. Grinding is driven by electric power. The average Dutch energy mix was applied to calculate GHG emissions for grinding. The applied value is 114 g CO_2 eq. $\cdot$ MJ^{-1}.

Table 3-2: The energy losses and required fossil inputs for different types of biomass pretreatment and the energy consumption for grinding of coal and pretreated biomass.

				Grinding			
Pretreatment	**Energy losses**	**Fossil input**	**Total**	**Low**	**Average**	**High**	**Unit**
Coal				18[d]	74	130[e]	MJ · t^{-1}
Chipping		249[a]	249	360	3240	4201	MJ · t^{-1}
Pelleting		464[b]	464	42	750	1500	MJ · t^{-1}
Torrefaction	1400	616[c]	2016	36[c]	648	1260[b]	MJ · t^{-1}
TOP	1400	695[c]	2095	22	389	756	MJ · t^{-1}

a vande Walle et al. (2007), b Uslu et al. (2008), c Batidzirai et al. (2013), d Lytle et al. (1992), e Phanphanich and Mani (2011).

3.2.4 Technical possibilities for biomass co-combustion in Dutch pulverised coal power plants

The Dutch Energy Agreement for sustainable growth aims to close five of the ten coal-fired power plants currently in operation (SER, 2013). This means that the GDF Maasvlakte, Amer 9, Hemweg 8, RWE-Eemshaven and MPP3 are theoretically available for co-combustion. The conversion efficiencies of these plants are: 46%, 40%, 41%, 46% and 46%, respectively (Peeters, 2013; Willeboer, n.d.; personal communication with R.M.J. Benders; RWE, n.d.; EON, n.d.). This paper applies a conversion efficiency for pulverised coal of 42%. Warringa et al. (2016) provide data based on their own calculations that give an estimate of the maximum share of biomass that can be co-combusted in these power plants. These values are, respectively 60%, 50%, 40%, 20% and 20%.

3.2.5 Modal energy intensity of transport modes

The low bulk density (< 750 kg · m^{-3}) of biomass causes maritime transport to be volume limited (Giuntoli et al., 2015). Based on data from Giuntoli et al. (2015) we argue that this also holds for truck transport when bulk densities are smaller than 300 kg · m^{-3}. The low bulk densities combined with low energy densities of biomass, make biomass transport from an energetic point of view uncompetitive with liquid or gaseous fossil alternatives transported through pipelines. Coal has a high energy and bulk density and is therefore not volume limited when it comes to transport[2]. When there is a volume limitation for biomass or a lower energy density compared to coal, the fossil inputs for biomass transportation are larger than for transport of coal per unit of energy transported. The modal energy intensity (MJ/tkm) was estimated for 40 t trucks with a net payload of 26 t and a volume of 90 m^3 and for the Supramax bulk carrier with 57000 t deadweight tonnage and a payload of 54000 t. A linear relation between mass load and energy consumption was assumed. Giuntoli et al. (2015) provide modal energy intensities (corrected in order to include return trips) for the 40 t trucks and Supramax bulk carrier, which were applied to determine two linear functions expressing the energy consumption of transport with different mass load or bulk density. Table 3-3 gives the required data (i.e. energy and bulk densities) to calculate the volume limitations. Subsequently, the modal energy intensity data from Giuntoli et al. (2015) were applied to determine two linear functions describing the energy use for transport. This was combined with the data on volume limitations in order to estimate the modal energy intensity, of both the truck and Supramax, loaded with coal or biomass, with different energy and bulk densities due to pretreatment. These specific results are presented in Appendix A. The GHG emissions from transport are based on the assumption that trucks are diesel driven and the

[2] Assuming an average bulk density of 825 kg · m^{-3} for coal; transport by bulk carrier and truck are both mass limited, since the bulk density is larger than 750 kg · m^{-3} and 300 kg · m^{-3} respectively.

Supramax bulk carrier uses heavy fuel oil (HFO). For HFO a value of 82.6 g CO_2 eq. · MJ^{-1} (calculated with data from Giuntoli et al., 2015) is applied.

Table 3-3: Input data for coal and biomass after different types of pretreatment.

	Energy density		Bulk density			
		Unit	Low	Average	High	Unit
Coal[a]	30	MJ · kg^{-1}	800	825	850	kg · m^{-3}
Chipping	14	MJ · kg^{-1}	200[a]	325	450[a]	kg · m^{-3}
Pelleting	17.7[a]	MJ · kg^{-1}	500[a]	575	650[a]	kg · m^{-3}
Torrefaction	18	MJ · kg^{-1}	230[a]	265	300[b]	kg · m^{-3}
TOP	18.4	MJ · kg^{-1}	750[a]	800	850[a]	kg · m^{-3}

a Uslu et al. (2008) b Tumuluru et al. (2011).

3.2.6 Conversion efficiency

Modern coal-fired power plants have electric conversion efficiencies over 46%. When biomass is co-combusted in a coal-fired power plant the overall efficiency decreases, due to deterioration of the boiler efficiency (Pronobis, 2006). Pronobis and Wojnar (2013), provided data about experimental boiler efficiency of the co-combustion of coniferous wood. In this article the reduction in boiler efficiency is equal to the reduction in conversion efficiency. Pretreatment of biomass, like torrefaction and TOP, results in a biogenic feedstock of which the chemical composition is more similar to coal. Therefore, this article argues that more pretreatment results in less deterioration of the boiler efficiency and thus a smaller decrease in overall process efficiency. Here, a 1% conversion efficiency drop for every 10% increase in co-combusted biomass was applied for wood chips (equation 3-1). This is in line with the data from Pronobis and Wojnar (2013). Torrefaction and TOP are assumed to have similar combustion performances after grinding. Pellets have lower moisture content than wood chips and are, therefore, assumed to have a combustion performance between wood chips and torrefied wood/TOP. For that reason, a higher conversion efficiency was applied for pellets, torrefied wood chips and TOP (equation 3-2 and 3-3), compared to dried wood chips. Based on these assumptions and the data from Pronobis and Wojnar (2013), equations 3-1, 3-2 and 3-3 were developed to calculate the conversion efficiencies of wood chips (3-1), pellets (3-2) and torrefaction and TOP (3-3).

$$f(x)_{\text{Wood chips}} = -10x + b \quad (3\text{-}1)$$
$$f(x)_{\text{Pellets}} = -7{,}5x + b \quad (3\text{-}2)$$
$$f(x)_{\text{Torrefied chips/TOP}} = -5x + b \quad (3\text{-}3)$$

Where x is the fraction of biomass co-combusted on an energy basis and b is the conversion efficiency of coal, which in this case was set at 42%. GHG emissions are determined by using a value of 94.1 g CO_2 eq. · MJ^{-1} (Penman et al., 2006) bituminous coal combusted.

3.2.7 Net renewable power production

We developed equation 3-4 to calculate the share of renewable power production in the total supply chain compared to a conventional reference chain with coal.

$$Erenewable\ power\ (\%) = \frac{Ebiomass-(Esupply\ chain-Ereference\ chain)}{Esupply\ chain} * 100\% \quad (3\text{-}4)$$

Where;

$E_{biomass}$ = The energy contained in the biomass,

$E_{supply\ chain}$ = The energy consumption in the whole supply chain,
$E_{reference\ chain}$ = The energy consumption in the coal reference chain.

3.2.8 Supply chain scenarios

Thirteen supply chain scenarios were analysed, which are graphically represented in figure 3-3. The stacked horizontal bars show the shares of biomass and coal in the different scenarios. The blocks show the different supply chains. The supply chains for route 6-9 and 10-13 are equal to the supply chains for route 2-5. Scenario 1 is the 100% coal supply chain reference scenario, where only coal is combusted. Scenarios 2-13 apply co-combustion of biomass. The shares of biomass vary from 10% to 60% on an energy basis. Routes 2-5 co-combust 10% biomass and vary the applied pretreatment technologies which are chipping only, chipping and pelleting, chipping and torrefaction and chipping and TOP. This is the same for routes 6-9 and 10-13 in which 25% and 60%, are co-combusted. For all supply chain scenarios the transport distances by truck and Supramax bulk carrier are set at 100 km and 8000 km.

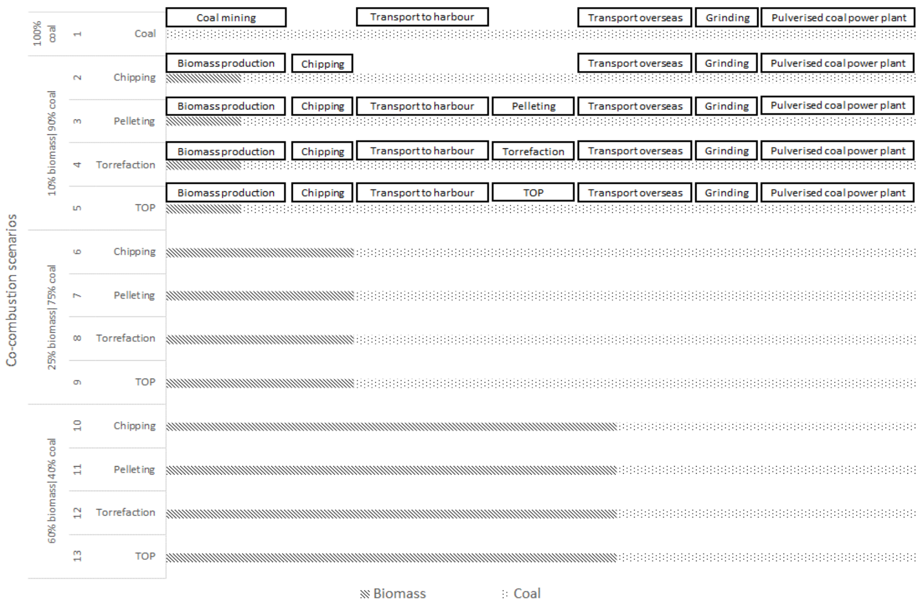

Figure 3-3: Overview of the analysed supply chain scenarios. The coal-based reference and biomass co-combustion scenarios.

3.3 Results

In the following section the results are presented. First, the biomass and coal requirements are calculated and expressed in kg · MJ_e^{-1} output. Second, the supply chain components are presented in three groups, namely production of biomass and mining and coal, transport and pretreatment. These results are expressed in MJ · MJ_e^{-1} output and g CO_2 eq. · MJ_e^{-1} output. The result section is finalised with an analysis of the whole chain and a summation of the results.

3.3.1 Biomass and coal requirements

Based on the conversion efficiencies (equation 3-1, 3-2 and 3-3), the energy density of the different fuels, and the energy losses for torrefaction and TOP (table 3-2), the biomass and coal requirements are calculated for all thirteen supply chains per MJ_e output (figure 3-4). These results show that with larger biomass fractions, the amount of biomass that has to be transported increases per MJ_e output. The differences in biomass demand, within the 10%, 25% and 60% supply chain scenarios, are due to pretreatment related energy losses in the biomass and the differences in conversion efficiency. The supply chain scenarios where 60% biomass is co-combusted require two times more mass to be transported than the 100% coal reference supply chain scenario.

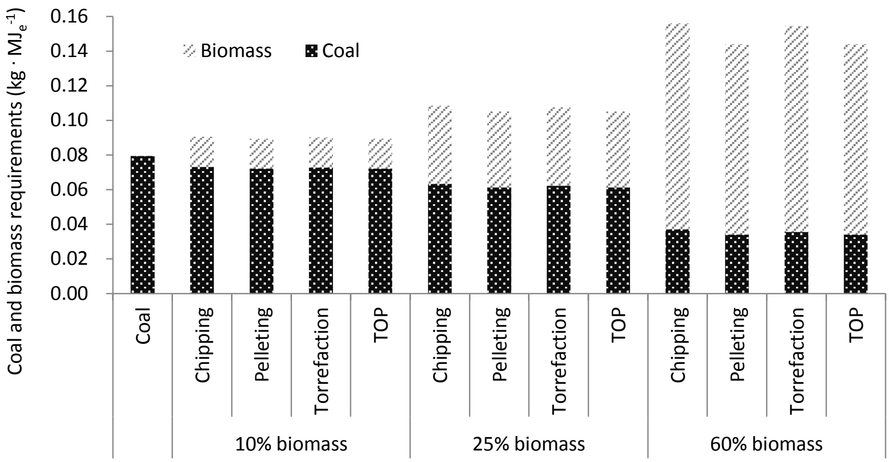

Figure 3-4: The biomass and coal requirements before pretreatment, for all 13 supply chains. Biomass quantities are on a dry basis (i.e. 20% moisture content).

3.3.2 Biomass production and coal mining

The feedstock production part of the supply chains with 10%, 25% and 60% biomass show an increase in energy consumption of respectively a factor 2, 4 and 8 compared to the coal reference (figure 3-5). The black dashed lines show the biomass and coal emissions. These are all fossil emissions related to the production and harvesting of biomass and mining of coal. The emission reduction through the combustion of biomass is taken into account in the combustion stage of the supply chain (section 3.5). Figure 3-5, therefore, represents the emissions related to fossil inputs required for biomass production and harvesting. The coal GHG emissions decrease, since the demand for coal decreases with increasing biomass demand. Emissions from biomass production and coal mining are in the same range per ton raw product. The low energy density of biomass, thus results in higher emissions per unit of energy produced. This effect becomes larger when increased quantities of biomass are co-combusted at the cost of coal. In the 25% and 60% supply chains the total GHG emissions are roughly twice as high as the reference.

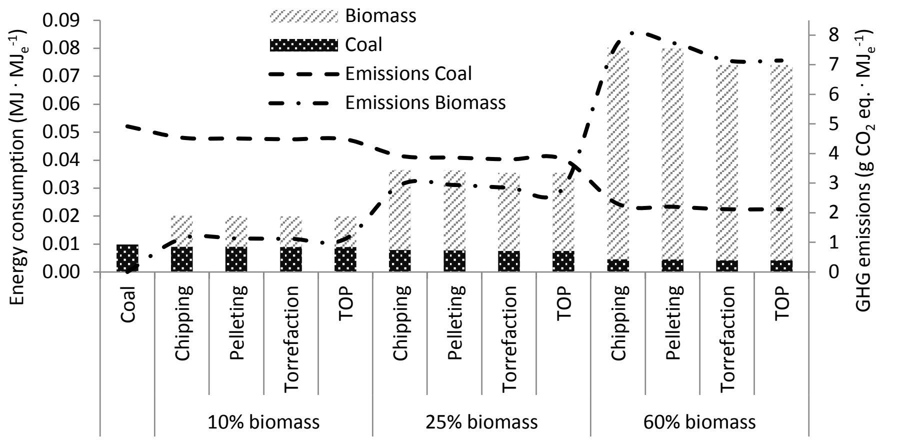

Figure 3-5: Energy consumption and GHG emissions for biomass production and coal mining for all 13 analysed supply chain scenarios.

3.3.3 Biomass and coal pretreatment

Figure 3-6 shows the energy losses in biomass due to torrefaction and TOP, the fossil energy input required for biomass pretreatment and the related fossil emissions. The energy requirement for biomass pretreatment is in the same range as biomass production (figure 3-5) and transport by Supramax bulk carrier (figure 3-9). This also holds for the related GHG emissions.

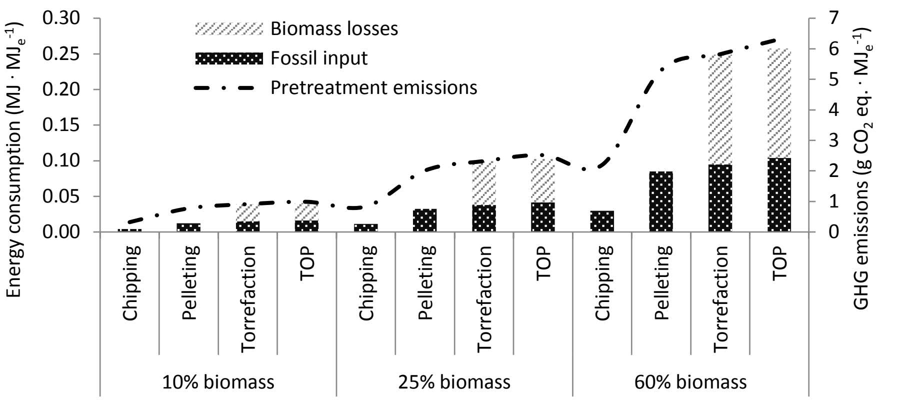

Figure 3-6: The energy consumption for biomass pretreatment, the accompanied energy losses in biomass and the GHG emissions related to biomass pretreatment. Values for pelleting, torrefaction and TOP also include chipping energy and emissions.

Figure 3-7 shows that the grinding performance of biomass is worse than the grinding performance of coal. Especially chipped wood shows large outliers compared to coal and more intensively pretreated biomass. A 9:1 coal to biomass energy ratio results in energy requirements for grinding, which are roughly similar for biomass and coal (i.e. when chipping is left out of the equation). More intensively pretreated biomass shows a doubling in GHG emissions in the 10%

biomass scenarios, the 25% and 60% scenarios show an approximate increase of a factor 5 and 10, respectively compared to the coal supply chain reference scenario.

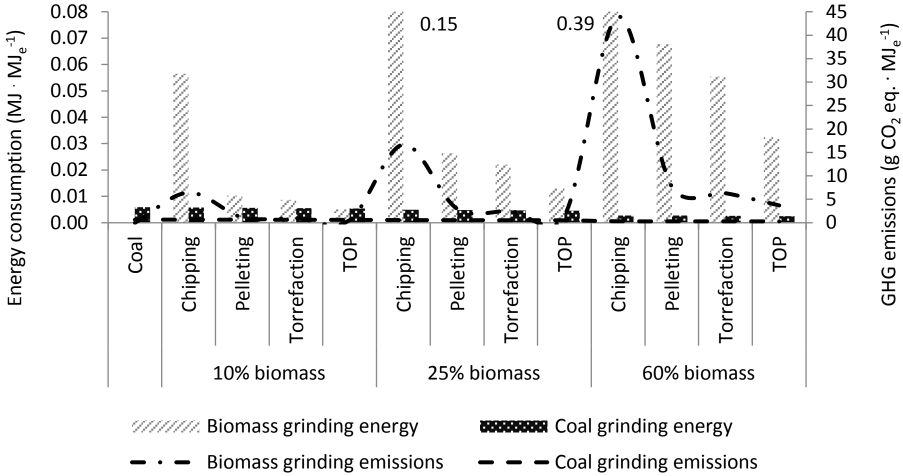

Figure 3-7: The energy consumption and GHG emissions related to biomass and coal grinding. The primary vertical axis is adjusted in order to clearly display the coal related values; the high values for chipping in the 25% and 60% supply chains are therefore presented with labels.

3.3.4 Transport performance by truck and bulk carrier

The calculations and results for the modal energy intensity of the two transport modes are presented in Appendix A. Load limitations for biomass are taken into account by applying the modal energy intensities from figure A-1 for coal and biomass transportation. Figure A-1 displays the calculated energy consumption of a 40t truck and Supramax bulk carrier for coal, wood chips, torrefied wood chips, pellets and TOP. Transport energy is displayed in figure 3-8 and 3-9. In all scenarios it becomes clear that the total energy consumption increases, compared to the 100% coal reference. Furthermore, figure 3-9 shows that TOP technology can reasonably compete with the coal reference for the 10% and 25% scenarios, during overseas transport. In addition, figure 3-9 clearly shows the effect of the load limitations for chipping and torrefaction, due to the low bulk density, especially in the 25% and 60% biomass chains.

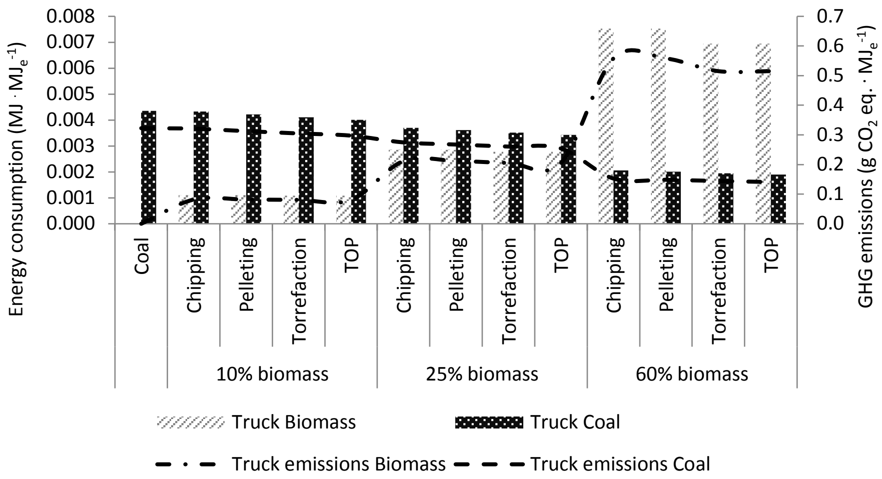

Figure 3-8: The energy consumption and GHG emissions related to transport by truck.

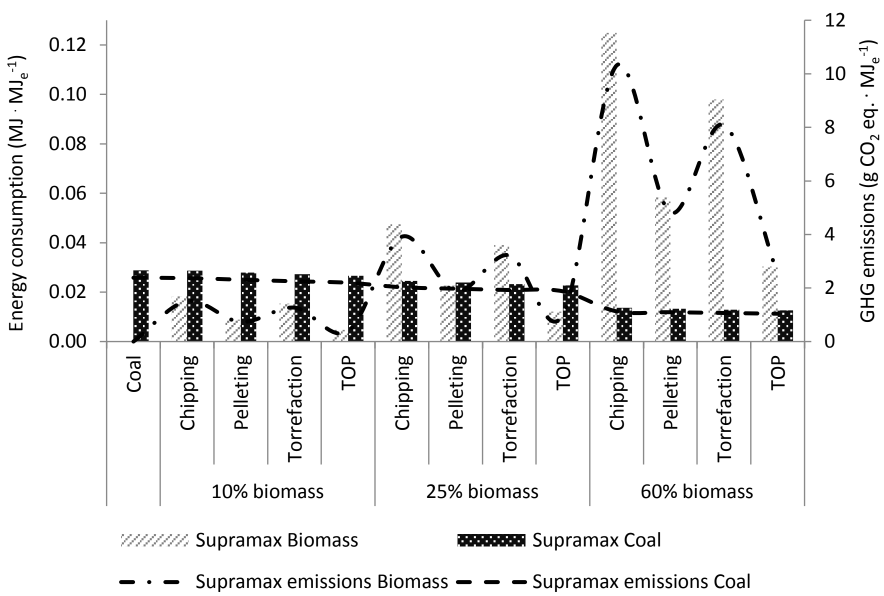

Figure 3-9: The energy consumption and GHG emissions related to transport by Supramax.

3.3.5 Energy consumption and emissions of the whole supply chain

Figure 3-10 shows that in every biomass supply chain scenario the overall system efficiency decreases, when compared to the combustion of the 100% coal chain. TOP has the best performance, but when substantial quantities (i.e. 60 % biomass) are co-combusted the system performance decreases with 7% compared to the reference. The other biomass supply chain scenarios have even lower system efficiency. Appendix B gives a detailed overview of the average total energy consumption and GHG emissions related to the whole supply chains excluding conversion into electric energy. The energy consumption for conversion can be calculated by taking the reciprocal value of the conversion efficiencies, which can be derived from equations 3-1, 3-2 and 3-3. The vertical axis starts at 1 MJ, since this is the part of the total energy used in the process to have 1 MJ_e output.

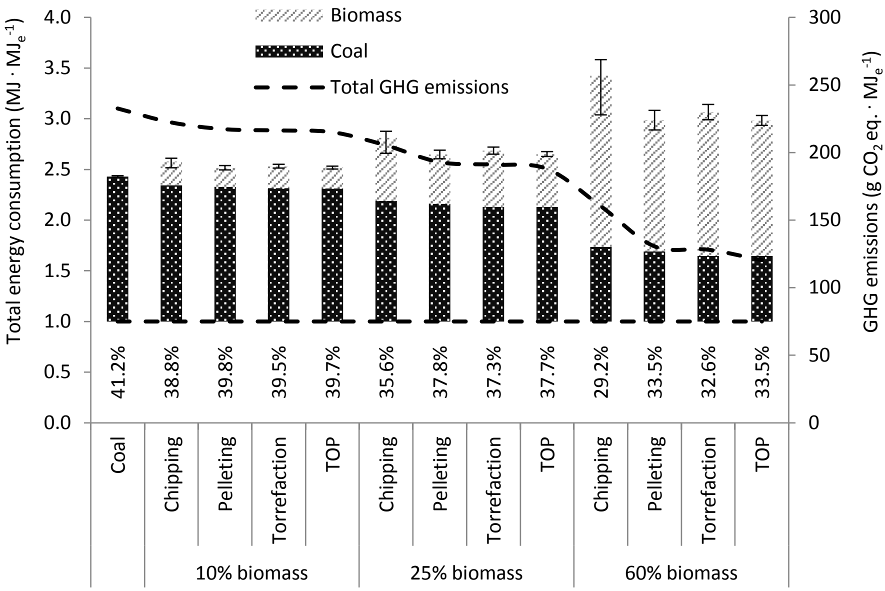

Figure 3-10: The total energy consumed for 1 MJ_e output in the whole supply chain including conversion. The graph starts at 1 MJ, in order to include the part of the feedstock that is converted to electric energy. The labels refer to the overall supply chain efficiency including conversion of the feedstock; the error bars represent the high and low values for the supply chain scenarios.

3.3.6 Summation of results

Figure 3-11 displays the performance of the indicators from the RED; energy reduction and consumption, energy efficiency and the share of renewable energy, which should result in a decrease in GHG emissions. It shows that when 10% biomass is co-combusted, the energy consumption of the supply chains increases in the same order of magnitude. Co-combustion of 10% chipped wood results in a 4% decrease in GHG emissions and a 4% increase in renewable power. TOP has the best performance with a decrease in GHG emissions of 7.5% and little over 6.5% renewable energy. The differences are quite small in the 10% biomass scenarios. The performance of wood chips becomes worse on a larger scale.

TOP has the smallest increase in energy consumption and the smallest decrease in overall energy efficiency. In the 60% biomass scenarios, TOP co-combustion leads to a 48% decrease in GHG emissions and an increase of 35% in renewable energy. Furthermore, the results show that, when biomass is co-combusted there is always reduced energy efficiency and increased energy consumption. Therefore, the indicators from the RED cannot be aligned in the case of biomass co-combustion. There is a reduction in GHG emissions, since biogenic emissions are not accounted for, and an increase in renewable energy, but the energy efficiency decreases and the energy consumption increases.

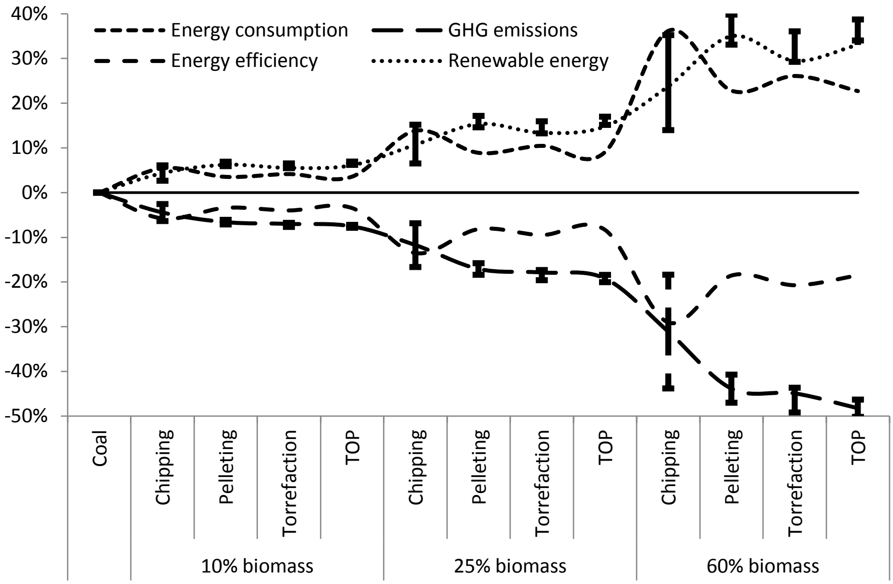

Figure 3-11: The relative change in GHG emissions, energy consumption, energy efficiency and renewable energy, compared to the 100% coal reference chain.

3.4 Discussion

Only direct energy use is taken into account in this paper, since this is the most important part. The inclusion of indirect energy may, however, alter the results. The design of the supply chains of coal and biomass differ in the feedstock production stage and the biomass pretreatment stage. Therefore, these two parts of the chain determine the potential difference in results, due to exclusion of indirect energy. It is probable that the inclusion of indirect energy therefore has a negative effect on the system performance of the biomass chains, since this also requires the construction and maintenance of pretreatment facilities. On the other hand there are the coal mining facilities, which have to increase production when biomass is not co-combusted. Also, the low and high values for grinding (table 3-2) deviate more from the average value, than other input data. This is due to a large variety in the available data in literature. Despite that, here it is argued that the average values are representative. Furthermore, when it comes to the calculated conversion efficiencies (equation 3-1, 3-2 and 3-3); there was no data available about the effect of biomass pretreatment and co-combusted quantities on power plant performance. Based on the data from Pronobis and Wojnar (2013) we argue that our estimates are reasonable. Hence, we took a maximum reduction in conversion efficiency of 1% for every 10% biomass co-combusted as a worst case for wood chips.

There is no supply chain scenario where co-combustion leads to energy savings or to a more energy efficient supply system. Co-combustion of biomass has a positive effect on CO_2 reduction on the full chain level. Low co-combustion levels, as considered in the Netherlands, are effective, but contribute little to the reduction of GHG emissions. TOP has the best performance, since the amount of renewables is the highest, the decrease in GHG emissions is the largest, the increase in energy consumption is the lowest and the energy efficiency shows the smallest decrease. However, TOP is also the most speculative, since there is currently no substantial market. A fair trade-off between the indicators of the RED is difficult to establish in the case of biomass co-combustion, since biogenic energy is approached as freely available (i.e. without taking possible scarcity issues into account) and biogenic emissions are approached as having no net impact. Global warming potentials are expressed in terms of 100 years and replacement of harvested biomass, and thus, sequestration of the CO_2 emissions from biomass, is not guaranteed. Focussing on one indicator from the RED may not necessarily lead to the most effective supply system for GHG emission reduction. Hence, this article shows that in all scenarios two (energy consumption and energy efficiency) of the three indicators perform worse than the reference coal supply chain scenario.

The system is demand driven (hence, the functional unit of 1 MJ_e output); the required quantities of biomass are therefore determined by the calculated conversion efficiencies based on equations 3-1, 3-2 and 3-3. The results show that at an increasing scale (from 10% to 60% co-combustion) the production of renewable power becomes less efficient. In our scenarios this means that every additional unit of biomass co-combusted is converted a little less efficient. Thus, co-combusting 10% biomass on six locations results in more renewable power than co-combusting 60% biomass in one location. For the reduction of GHG emissions this effect is reversed, since higher shares of biomass require relatively larger quantities of biomass at the cost of coal. Table 3-4 gives an overview of this effect for our scenarios. It shows that for increasing levels of co-combustion, the reduction in GHG emissions increases when additional units of biomass are co-combusted. It also shows that for every additional unit of biomass co-combusted the amount of renewable energy decreases. Increasing the share of co-combusted biomass results in an increase in performance when it comes to GHG emission reduction; it results in a decrease in performance when looking at the amount of renewable energy production. This phenomenon is worth mentioning, but in this article it is negligible. A quadratic or exponential decrease in conversion efficiency, instead of a linear decrease can cause this effect to increase, when larger biomass fractions are co-combusted. Data addressing the effect of biomass co-combustion on conversion efficiency was difficult to find and requires more research, since it could change the results of this article. Our data are in line with Pronobis (2006) and Pronobis and Wojnar (2013). However, Li et al. (2012) present discrepancies in boiler efficiency for co-combustion of torrefied biomass that show a quadratic relation, which could worsen the abovementioned effects.

Table 3-4: Performance of the different scenarios per MJ of biomass expressed for GHG emissions and renewable electricity.

	Scenarios			
	10%	**25%**	**60%**	
Chipping	-42.38	-43.10	-43.38	
Pelleting	-63.33	-63.75	-63.75	$g\ CO_2\ eq. \cdot MJ_{biomass}^{-1}$
Torrefaction	-67.46	-67.74	-67.90	
TOP	-72.78	-72.86	-72.92	
Chipping	0.19	0.18	0.17	
Pelleting	0.27	0.26	0.24	$MJ_{renewable} \cdot MJ_{biomass}^{-1}$
Torrefaction	0.24	0.24	0.23	
TOP	0.27	0.26	0.25	

3.4.1 Sensitivity analysis

Despite some large variations in the estimated energy consumption, especially grinding (see table 3-2), but also for coal mining and transport by bulk carrier, figure 3-11 shows that the error bars are in the order of a few percent. The negative values for the error bars were constructed by taking the high values for the supply chain scenarios combined with a 2% conversion efficiency drop (i.e. *b* in equation 3-1, 3-2 and 3-3). The positive values for the error bars were constructed by taking the low values for the supply chain scenarios combined with a 2% conversion efficiency increase. By this approach, the most extreme cases are shown. The error bars in figure 3-11 show that the range in the results is small except for chipped wood. Chipping is, together with torrefaction, subject to substantial load limitations in overseas transport and chipping has the worst grinding performance. Furthermore, the conversion efficiency of wood chips is assumed to be the lowest.

3.5 Conclusion

This paper analysed the performance of supply chains for biomass co-combustion in a pulverised coal power plant. From an energy and GHG emissions perspective, the production stage of biomass cannot compete with bituminous coal mining. Coal mining is more energy and CO_2 efficient than biomass production, harvesting and chipping. However, in our case we allocated all fossil inputs and emissions related to biomass production to the supply system.

Energy consumption and GHG emissions related to biomass pretreatment have the worst performance in the cases of TOP and torrefaction; this also holds when the losses in energy content of the biomass are neglected and only the fossil input is taken into account. Despite a reduction in the energy requirement for grinding due to biomass pretreatment, the energy consumed for the grinding of biomass is higher than the grinding energy of coal. From a whole chain perspective TOP performs the best, because the conversion efficiency to electricity is higher and the transport requirements are lower.

The mass load limitations for the chosen transport modes are the largest for chipped and torrefied wood when it comes to truck transport. For transport over water, pellets are also limited by mass, therefore, only TOP can directly compete with coal transportation. The effect of the mass load limitations of chipped and torrefied wood are the most prominent in transport by bulk carrier. Furthermore, there is an increase in transport related GHG emissions for all scenarios.

Results indicate that the three indicators, renewable energy, energy efficiency and energy reduction cannot be aligned in the case of biomass co-combustion. The energy efficiency decreases in all supply chains; the energy consumption increases in all supply chains. Wood chips, torrefied wood chips, pellets and TOP, in the 10% biomass scenarios, show a decrease in emissions and a positive value for renewable energy, but the effect is little. This suggests that the introduction of bioenergy, in the energy system, does not necessarily lead to a system where energy is saved or used more efficiently, and there is also no guarantee that the optimal reduction in GHG emissions is established. This is in line with Pierie et al. (2016), who emphasise that the application of a renewable resource is not always the most environmentally sustainable solution. The low co-combustion levels are effective to reduce GHG emissions, but the margins are small. When including indirect energy, the possibility of a larger conversion efficiency drop than calculated and chain components performing worse than expected may result in a negligible GHG reduction or even an increase compared to the coal supply chain reference.

The indicators from the RED cannot be aligned (figure 3-11); this is emphasised by table 3-4. When biomass is regarded as scarce, one should focus on the most efficient use of biomass and thus on co-combustion of small quantities, or no co-combustion at all. When biomass is regarded as abundant, one should focus on GHG reduction, and thus, on co-combustion of large shares of biomass.

4

Synthetic Natural Gas Supply Chain Analysis

Environmental and energy performance of the biomass to synthetic natural gas supply chain.

Abstract
A quarter of the total primary energy demand in the European Union is met by natural gas. Synthetic natural gas produced through biomass gasification can contribute to a more sustainable energy supply system. A chain analysis of the energetic performance of synthetic natural gas where the upstream, midstream and downstream part are included, has not been found in literature. The energy performance of the possible large scale application of synthetic natural gas is therefore unsure. A model was designed to analyse the performance of the biomass to synthetic natural gas chain and to estimate the effect of 1% synthetic natural gas in the energy system. A break-even distance is introduced to determine whether it is energetically feasible to apply pretreatment. Results show that torrefaction and pelleting are energetically unfeasible within the European Union. Emissions can be reduced with almost 70% compared to a fossil reference scenario. Over 1.2 Mha is required to fulfil 0.25% of the total primary energy demand in the European Union.

Keywords
Synthetic Natural Gas, Biomass gasification, Chain analysis, Break-even transport distance, Supply chain optimisation.

Chapter information	
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GAS

4.1 Introduction and background

Approximately 25% of the total primary energy demand in the European Union (EU) is satisfied by natural gas. Despite the estimated decrease in energy demand, the consumed quantities of natural gas are expected to increase up to 30% in 2035 (Priddle, 2013). The EU has set objectives to achieve a share of 20% of energy from renewable energy sources in the gross final consumption in 2020 (European Commission, 2009). Eurostat provides intermediate results on these objectives (Eurostat, 2014a). The share of renewables in the gross final energy consumption was 14.1% in 2012. This means that from this date forward the annual increase should be at least 4.5% in order to meet the 20% objective. Despite possible adverse effects, on amongst others, crop prices, food supply, biodiversity and forest protection, biomass contributes for almost 66% to the primary production of renewable energy in 2012 (Eurostat, 2014b). Applying biomass for energetic purposes should therefore be done as efficient as possible. An example of more efficient use of biomass, is electricity production through biomass gasification combined with a gas turbine (35% to 40%), which is energetically advantageous, compared to combustion of biomass (25% to 30%) (Negro et al., 2008). Synthetic natural gas (SNG) produced through biomass gasification followed by a methanisation step can contribute to the targets set by the EU for the reduction of the emissions of fossil carbon, since it has a renewable origin. Besides this, due to similar characteristics SNG can be mixed with natural gas, which is advantageous since there is a large gas infrastructure present (Zwart et al., 2006).

The gasification technology can be applied on a large scale (i.e. several hundreds of MWs). Given the high European green gas ambitions and the presence of a natural gas grid, suitable for distribution of SNG, there are opportunities for the large scale application of biomass gasification for SNG production. In line with the expected increase in natural gas use (Priddle, 2013) this paper argues that since, natural gas is the cleanest fossil fuel and therefore it has better long term opportunities than coal and oil, especially when large scale injection of a green gas, such as SNG, is applied. This paper argues that the environmental and energy performance of such a large system are currently unknown for two reasons. First, most literature only studies the (partial) upstream chain and not the conversion or downstream distribution part of bioenergy systems (see for example Allen et al., 1998; Caputo et al., 2005; Rentizelas et al., 2009). Second, there are only a few studies available that specifically look at SNG or biomass gasification from a system perspective. The study by Uslu et al. (2008) does look at large scale bioenergy supply systems, but only includes the upstream chain including pretreatment, but it excludes biomass conversion to a liquid or gaseous fuel. Besides this, the study is mostly focused on the cost aspect of such a supply system. The same arguments also hold for the more recent study by Lin et al. (2016), whom look at pretreatment and long distance transportation. Two recent life cycle analyses (LCAs) are available (Boschiero et al., 2016; Granda-Marulanda et al., 2015) of which the first studies biomass gasification for heat and power production on a small scale. The second study does focus on SNG production, but also studies a small scale system. Another recent study by Sriwannawit et al. (2016) explores the economic feasibility of biomass gasification systems in Indonesia. They focus on the economic viability of biomass gasification, on a small scale, for electricity production in rural areas. In these studies, the energy performance is underexposed, since those LCAs (Boschiero et al., 2016; Granda-Marulanda et al., 2015) mainly focus on the environmental impact of systems or services. The study by Sriwannawit et al. (2016) uses locally available biomass resources, which is not in line with our research where we assume that biomass has to be transported over long distances. The studies that do take into account long distance transportation, exclude the conversion step to power, gas or a liquid energy carrier.

This study argues that the conclusion by Iakovou et al. that few studies focus on supply chain issues in the context of the whole chain is still valid (Iakovou et al., 2010). Therefore, the environmental and energy performance of the whole chain of large scale biomass gasification for SNG (including biomass production, harvesting, handling, storage, intermediate transport, pretreatment, transport to conversion plants, conversion, distribution to the end-user and finally end-use), is not well known. This research studies options for centralised large scale biomass gasification for the production of SNG, in order to optimally exploit the existing natural gas infrastructure, distribute energy sources, fulfil environmental objectives and maintain a strong market position on the long term.

The main aim is to analyse the environmental impact and energetic performance of SNG, when SNG replaces 1% of the current natural gas consumption in the EU28 by analysing the upstream and midstream part of the chain. This equals 0.25% of the final gross energy consumption, which is no more than 11% of the needed annual increase to reach the objective of 20% renewables in the final gross energy consumption in the EU in 2020. In order to determine the performance of the biomass to SNG to end-use chain, a chain analysis was done.

4.2 Methods

4.2.1 Model description

A dynamic model is developed to simulate SNG routes and calculate its environmental and energetic performance. The model is divided in three parts: the upstream, midstream and downstream part of the chain. Figure 4-1 gives an overview of the model. Biomass is produced and harvested; subsequently, it is pretreated and stored on-site. Transport is applied to a secondary pretreatment facility when pelleting or torrefaction is applied. Subsequently, the pretreated biomass is stored at the conversion site where SNG is produced. After production, SNG is injected into the grid, mixed and transported to the end-user.

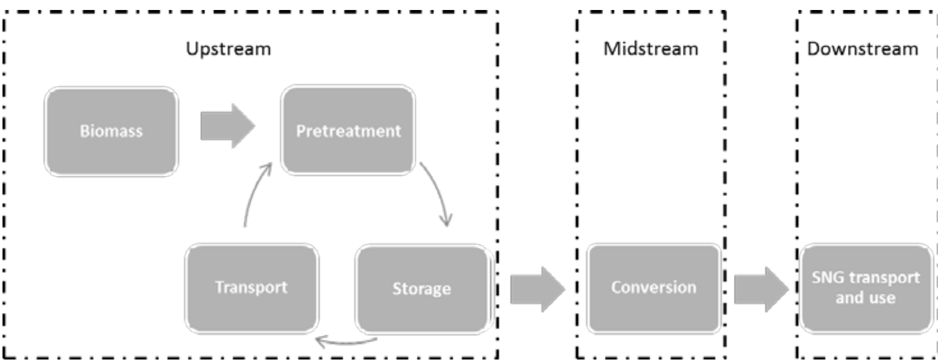

Figure 4-1: Overview of the different process steps in the applied model.

4.2.2 Performance indicators

Energy performance indicators are numerous in literature. This research restricts itself to the use of the Energy Efficiency (EE) which is defined as the ratio of usable energy (i.e. SNG) produced to the energy contained in the biomass feedstock (Djomo et al., 2011). The EE is applied to determine the conversion efficiency of the whole biomass to SNG supply chain. It is a representation of the energy content lost due to processing of biomass in secondary and/or tertiary products and the external fossil inputs. The Energy Ratio (ER) is defined as the total usable energy produced by the system, divided by the total energy input to drive the system. An ER > 1 implies that the energy input is smaller than the produced energy output (Djomo et al., 2011). The equations for the ER and the EE are respectively taken from Matthews (2001) and Rafaschieri et al. (1999) and subsequently adjusted to the system described in this paper.

$$EE = \frac{E\ sng - E\ fossil\ input}{E\ biomass} \tag{4-1}$$

$$ER = \frac{E\ sng}{E\ fossil\ input} \tag{4-2}$$

Where;

E_{sng} = The energy contained in the SNG delivered to the grid,
$E_{fossil\ input}$ = The amount of fossil energy used in the upstream process,
$E_{biomass}$ = The energy contained in the biomass at harvest.

The environmental performance is measured with two indicators, namely land use in hectares and GHG emissions in CO_2 eq. · MJ^{-1} SNG supplied. In these CO_2 equivalents, CO_2, CH_4 and N_2O are taken into account, since these are the most common GHGs related to agriculture (IPCC, 2006). CH_4 consumed during fertiliser production is integrated in the calculations. This value includes all fossil inputs for nitrogen fertiliser. The needed equation to calculate the reduction in GHG emissions relative to the conventional fossil chain is derived from Hoefnagels et al. (2010).

$$GHG\ reduction = \frac{GHG\ emission\ conventional\ chain - GHG\ emission\ bio\ chain}{GHG\ emission\ conventional\ chain} \tag{4-3}$$

4.3 Scenarios and boundaries

The chain analysis requires an overview of the steps in the biomass to SNG to end-use chain. These are all the steps in which energy is consumed. The chain starts at the site where biomass is produced and subsequently transported to and converted at the biomass gasification site. After this the SNG is distributed towards the end-user and combusted. In the following, the different steps in the biomass supply chain are elaborated upon.

4.3.1 Production systems

The difference in net yield between intensive and extensive systems can be a factor 2.3-8 for short rotation poplar depending on the region in which they are produced in Europe (Nonhebel, 2002). Short rotation poplar production can be, to some extent depending on the system, accompanied with planting, fertilisation, crop protection, weeding, irrigation and harvesting. When taking these individual steps into account it appears that irrigation (which is left out in this paper), fertilisation and harvesting have a significant impact compared to the other steps. Fertilisation can be responsible for over 40% of the total fossil inputs in the intensive biomass production system (Nonhebel, 2002).

This research applies two biomass production systems. The first is an intensive production system with nitrogen fertilisation based on the NWE_{high} scenario developed by Nonhebel and a plantation lifetime of 20 years (Nonhebel, 2002). Yields are assumed to be 10 t · ha^{-1} yr^{-1} on a dry basis (db); this is in the same range as values provided by Nonhebel (2002) and Sannigrahi et al. (2010). The second is an extensive system in which the incremental growth of European forests is harvested for energetic purposes in which the poplar yields are assumed to be on average 2 t · ha^{-1} yr^{-1} db. Moisture content of the harvested wood is assumed to be 50%, with a primary energy density of 10 MJ kg^{-1}. The differences between the production systems are in fossil energy input, but also in the dispersion of biomass. The intensive scenarios apply 70 kg N · ha^{-1} yr^{-1} and use the emission factor given by the IPCC (2006) for N_2O emissions. Therefore, the emissions for N_2O are estimated at 0.7 kg · ha^{-1} yr^{-1}. Land preparation, harvesting and fertilisation are taken into account in the intensive scenarios. The extensive scenario harvests the increment rate of existing forests and therefore does not take land preparation and fertilisation into account. Subsequently, handling, transport, pretreatment, storage and conversion to SNG are taken into account for all scenarios.

4.3.2 Pretreatment options

This research considers four pretreatment options, on-site drying, on-site chipping, torrefaction and pelleting, further down the chain at an intermediate location. Torrefaction requires no fossil inputs, since approximately 10% of the energy contained in the biomass is used for the process whilst simultaneously 30% of the mass is lost (Tumuluru et al., 2011). This results in an increase in energy density of a factor 1.3. The energy losses do result in increasing land requirements. Pelleting requires external inputs in order to apply the pressure and temperature required to produce them. Pellet production is assumed to be based on natural gas (Mani, 2005). A reduction to a moisture content of 10% on a wet basis (wb) is applied for pellets based on data from Uslu et al. (2008).

4.3.3 Storage and seasonality

Due to the seasonality of the growth of biomass and pretreatment, storage is required in order to foresee in year-round supply to the conversion facility. After harvesting in winter, log-wood needs an on-site drying period in order to reach a moisture content below 30% wb. At this point the logs are suitable for chipping and further processing (Aebiom, 2008). From an energetic point of view, on-site drying is required, since it increases the energy density of the wood. A nine months on-site drying period is assumed to be enough to reach a moisture content below 30% wb (Aebiom, 2008), which is a rate at which wood is further transported. This research assumes that a moisture content of 20% wb can be achieved by passive drying. Chipped biomass with 20% or less moisture is suitable for gasification.

4.3.4 Biomass gasification

The Energy research Centre of the Netherlands (ECN) has developed the MILENA biomass gasification process, which is schematically represented in figure 4-2 (van der Meijden, n.d.). Biomass is fed into the riser/gasifier simultaneously with superheated steam. Opposite to the biomass, sand is injected into the riser as a bed material. The biomass decomposes partially into gas and is removed as producer gas. Tars, dust and bed material come down due to reduced velocity and are recirculated. The tars and dust are combusted in order to heat the bed material (van der Meijden, 2011). When impurities are removed the gas can be upgraded to SNG by a methanation step at a total efficiency of about 70% depending on the quality of the feedstock. For woody biomass with 20% moisture wb an efficiency of 70% is applied. For pellets and torrefaction respectively 72% and 72.5% are applied as conversion efficiencies, due to a decrease in moisture towards 10% and 3% wb. The latter might be on the high side because of a reduction in the quantity of hydrocarbons present in the feedstock (B. van der Drift, personal communication, August 14, 2014).

4.3.5 SNG injection and distribution

At high pressures (up to 40 bar) the biomass to SNG yield can be 70%. Therefore, this research does not take into account energy use for injection into the high pressure transmission system, since it assumes that it has sufficient pressure in order to be fed directly into a pipeline system, similar to natural gas from a wellhead (Devold, 2013). Besides that, it is similar to storage systems that operate at higher pressure than the pressure used in the transmission grid, in order to apply free flow when necessary (B. Kootstra, personal communication, May 5, 2014). Injection into the high pressure grid is, despite its higher energy cost, done for multiple reasons. The high pressure transmission grid is an active grid which means it is bidirectional. Furthermore, this grid is able to handle different gas qualities and is used in the Netherlands to supply energy to large industrial users (Weidenaar et al., 2011). Injection capacity in this grid is larger than in the low pressure distribution grid.

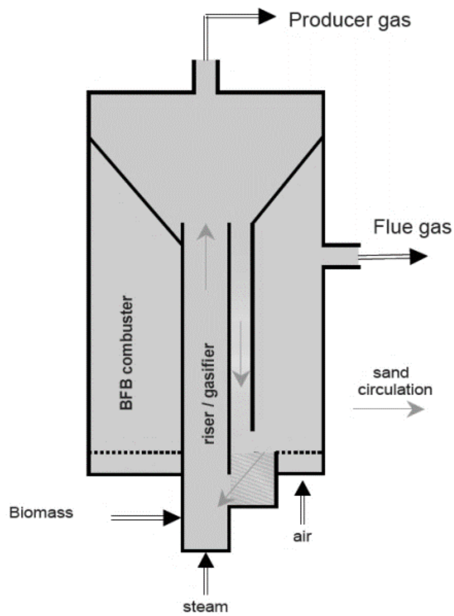

Figure 4-2: Schematic overview of the MILENA gasification process. Taken from van der Meijden (n.d.).
BFB: Bubbling Fluidised Bed

4.3.6 Transport efficiency

During pretreatment and conversion the energy content of the biomass changes. According to research by van der Drift et al. (2005) the process efficiency from pretreated biomass to SNG is approximately 70%. In order to determine the overall energetic efficiency of the supply chain the losses due to pretreatment should be taken into account. Assuming that no biomass is lost in the process of handling, storage and transport, the energy content only decreases due to torrefaction. It is possible to compensate for these losses, during transport. Hence, about 90% of the energy contained in the biomass remains after torrefaction, whilst 30% of the mass is lost (Tumuluru et al., 2011) which can be advantageous in transport when the energy consumption for transport is reduced compared to untreated biomass. Furthermore, torrefaction requires 5% more biomass when compared to a chain with only drying and chipping. For pelleting this is 3% less, because the conversion efficiency to SNG is higher than for dried and chipped biomass. A decrease to a moisture content of 10% wb is assumed for pelleting. Therefore, the energetic feasibility of torrefaction and pelleting are determined by the transport distance, the changing energy density of pretreated biomass and the used transportation type after torrefaction or pelleting. Equations 4-4 and 4-5 are applied to determine the break-even distance for torrefied biomass with dried biomass (20% wb) as a reference. The break-even distance for pelleting can be calculated analogue to torrefaction.

Equation 4-4 was applied to calculate the energy required for transport when fresh or pretreated biomass is used. Equation 4-5 was applied to calculate the energy required for the aforementioned pretreatment technologies.

$$E_T = \sum\left(\mathrm{E}_{\mathrm{TM}_n} \frac{\mathrm{Bio_{di}}}{\eta \mathrm{C}_x \,.\, \mathrm{HV}_i} \mathrm{D}_n\right) + \mathrm{E}_{\mathrm{h}_i} \quad (4\text{-}4)$$

$$E_p = \frac{\mathrm{Bio_{di}}}{\eta \mathrm{C}_x \,.\, \eta \mathrm{P}_i} - \frac{\mathrm{Bio_{di}}}{\eta P_i} \quad (4\text{-}5)$$

Where;

E_T	= The total energy consumed to transport biomass ($MJ \cdot yr^{-1}$),
E_p	= The total energy consumed by pretreatment ($MJ \cdot yr^{-1}$),
E_{TMn}	= The modal energy intensity of transport mode *n* (MJ/kg·km),
Bio_{di}	= The demand for biomass at the conversion plant, where *i*, when applied, refers to the pretreatment technology ($MJ \cdot yr^{-1}$),
ηC_x	= The efficiency of the applied conversion technology *x*, dependent on the applied pretreatment technology *i* (%),
HV_i	= The LHV of biomass *i* ($MJ \cdot kg^{-1}$),
D_n	= The transport distance for transport mode *n* (km),
E_{hi}	= The total energy consumption for handling/intermodal transfer, where *i*, when applied, refers to the pretreatment technology ($MJ \cdot yr^{-1}$),
E_p	= The sum of the energy consumed in biomass, due to pretreatment ($MJ \cdot yr^{-1}$),
ηP_i	= The energetic efficiency of pretreatment technology *i* (%).

When pretreatment is applied, the sum of equations 4-4 and 4-5 was taken to calculate the energy requirement for transport and the energy required for pretreatment of biomass. Solving the equation $E_{T\ Fresh} = E_p + E_{T\ pretreatment}$ gives the unknown variable D. This is the so-called break-even transport distance. We apply the modal energy intensity (MJ/tkm) to describe the energy consumption for transport. To estimate the break-even distance for the studied chains, the average energy intensity for the combination of transport modes was determined based on the energy consumption and transport distance per mode.

4.3.7 System boundaries

The consumption of water, the effect of biomass cultivation on groundwater, nutrient loading and emissions due to indirect land use change (ILUC) are not taken into account. The downstream part of the SNG chain is equal to the downstream natural gas chain and is therefore not taken into account. Combustion at the end-user is taken into account for the reference scenario when considering CO_2 emissions, since they have a fossil origin.

4.3.8 Reference scenario

The net efficiency of natural gas production (1- (losses + energy industry own use) / production) in Europe is 90.7% based on data from 2010 (IEA, 2012). This means that for one unit of energy delivered 0.1025 units are needed. Natural gas emissions are taken from Harrison et al. (1996), who estimate that 1.4% ± 0.5% of the gross natural gas production is emitted during production, processing, distribution, transmission and storage. Assuming that 90% of the high calorific natural gas consumed in industry consists of methane, this shows that methane emissions are in the order of 1.26% of the gross natural gas production. This research assumes that natural is gas combusted in order to use it for production, processing, distribution, transmission and storage of natural gas and therefore results in emissions of CO_2; in literature a value of 56.1 g $CO_2 \cdot MJ^{-1}$ is often applied (Quaschning, 2013). Indirect energy is not taken into account for the production of the wellhead and processing plants, distribution and storage. This research tries to replace 1% of the natural gas consumption in the EU; emissions from the wellhead and processing plant are therefore marginal and the emissions from distribution and storage are the same for SNG.

The energy efficiency for the natural gas chain is calculated by equation 4-6; the energy ratio by equation 4-7.

$$EE = \frac{E\ natural\ gas\ delivered - E\ fossil\ input}{E\ gross\ natural\ gas\ produced} \tag{4-6}$$

$$ER = \frac{E\ natural\ gas\ delivered}{E\ fossil\ input} \tag{4-7}$$

$E_{natural\ gas\ delivered}$ = The amount of natural gas delivered to the grid,
$E_{fossil\ input}$ = The amount of fossil energy used in the upstream process,
$E_{gross\ natural\ gas\ produced}$ = The amount of natural gas produced in order to deliver $E_{natural\ gas\ delivered}$ to the grid.

4.3.9 Scenario delineation

All scenarios use the same biomass transport distances which are 20 km for forwarding and 3000 km towards the conversion plant. An average of 3000 km is assumed to be realistic within the borders of the EU28. When a combination of transport types is applied, this research assumes truck transport of 500 km combined with 2500 km over water, for which a barge is applied, suitable for short sea distances. Table 4-1 shows the different routes simulated to fulfil the scenario of 1% SNG. Four types of pretreatment are taken into account, namely drying, chipping, torrefaction and pelleting. A ceteris paribus approach is applied in which one chain parameter is changed in order to determine its impact on the efficiency of the whole chain and to make its impact comparable with alternative supply chains. The differences in these scenarios are in the transport distances, transport modes, the amount of handling (i.e. loading and unloading movements), energy density of biomass due to varying pretreatment and the total biomass demand determined by the changing properties of biomass, depending on the chosen pretreatment.

The scenarios are designed in such a way that an analysis can be done of the energetic performance and environmental impact of the production systems, the transport modes and pretreatment options. Besides this, an analysis of the energetic feasibility of torrefaction and pelleting is done, based on break-even distances for transport.

Table 4-1: Upstream biomass to SNG routes.

	Production	Forwarding	Onsite pre-treatment	Transport	Intermediate pre-treatment	Transport
0	Extensive	20 km	Chipping Drying	Truck 3000 km Netherlands		
1	Intensive	20 km	Chipping Drying	Truck 3000 km Netherlands		
2	Intensive	20 km	Chipping Drying	Truck 500 km Intermediate		Barge 2500 km Netherlands
3	Intensive	20 km	Chipping Drying	Truck 500 km Intermediate	Torrefaction	Truck 2500 km Netherlands
4	Intensive	20 km	Chipping Drying	Truck 500 km Intermediate	Torrefaction	Barge 2500 km Netherlands
5	Intensive	20 km	Chipping Drying	Truck 500 km Intermediate	Pelleting	Barge 2500 km Netherlands

4.3.10 Input data

The input data for the model are displayed in table 4-2. It gives an overview of the parameters taken into account and their values. A value of 35.86 $MJ \cdot l^{-1}$ is applied for the energy density of diesel. Indirect energy use for machinery is not taken into account for loading, handling and pretreatment. This means that indirect energy needed for manufacturing and maintenance of loading and handling equipment and for the construction of pretreatment facilities, are left out. Furthermore, the indirect energy for storage is left out, which means that only loading and unloading are taken into account. Emissions from indirect energy use for transport are based on natural gas.

4.4 Results

The results are divided in the energetic and environmental performance. The energetic performance takes into account the EE and ER. Therefore, the results needed are the consumption of fossil energy for all supply chain elements and the energy lost in the biomass due to pretreatment and conversion steps.

Table 4-2: Input data for the simulations addressing energy consumption and GHG emissions.

Process or product	Specific process or product	Direct	Indirect	Source	Remark
Ploughing and preparation		1327 MJ ha^{-1} 20 yr^{-1}		Vande Walle (2007)	During establishment phase; production phase is 20 years
			324 MJ ha^{-1} 20 yr^{-1}	Hülsbergen et al. (2001)	Natural gas based
Crop protection		215 MJ ha^{-1} yr^{-1}		Dijkman and Benders (2010)	Only applicable for intensive system
			200 MJ ha^{-1} yr^{-1}	Nonhebel (2002)	Three rounds yr^{-1}, indirect energy per round
Harvesting		73 MJ t^{-1}		Dijkman and Benders (2010)	Indirect energy is assumed to be similar to fertiliser application and derived from natural gas
			28 MJ ha^{-1} yr^{-1}	Dijkman and Benders (2010)	
Forwarding		3.4 MJ/tkm			Assumed to be half as efficient as truck transport
			0.92 MJ/tkm		
Fertiliser	Application	180 MJ ha^{-1} yr^{-1}		Dalgaard et al. (2001)	Value between Dalgaard et al. (2001) and Nonhebel (2002). Manufacture and maintenance of machinery is natural gas based
			28 MJ ha^{-1} yr^{-1}	Hülsbergen et al. (2001)	
	Production		35.1 MJ kg^{-1} N	Hülsbergen et al. (2001)	Includes indirect energy for feedstock production and CH_4 feedstock
Loading	Biomass	10.8 MJ t^{-1}		Vande Walle (2007)	
Pre-treatment	Chipping	249 MJ t^{-1}		Vande Walle (2007)	Original in MJ kg^{-1} DM, assumed moisture content 50%
	Pelleting	464 MJ t^{-1}		Uslu et al. (2008)	
Transport	Truck	1.68 MJ/tkm	0.46 MJ/tkm	Bos (1998) and van den Brink and van Wee (1997)	

	Barge shortsea	0.28 MJ/tkm	0.03 MJ/tkm	Bos (1998) and van den Brink and van Wee (1997)	
Emissions	**Specific emission**	**Direct**	**Indirect**	**Source**	**Remark**
Fertilisation (N)	CO_2		2.2 kg CO_2 kg^{-1} fertiliser	Snyder et al. (2009)	Production phase
	N_2O	1 % N_2O kg^{-1} N		IPCC (2006)	After application
Pelleting	Emissions CO_2	190 g CO_2 kg^{-1} pellets		Mani (2005)	Production based on natural gas
	Emissions CH_4	0.92 g CH_4 kg^{-1} pellets		Mani (2005)	
Chipping	Emissions CO_2	18 g CO_2 kg^{-1} chips			Diesel engine
Diesel combustion	Emissions CO_2	73.54 g CO_2 MJ^{-1}		Eucar (2007)	Equals 2637 g CO_2 l^{-1}
Natural gas combustion	Emissions CO_2	56.1 g CO_2 MJ^{-1}		Quaschning (2013)	
Scenario input general	**Specific input**	**Direct**	**Indirect**	**Source**	**Remark**
Global Warming Potential 100 yr^{-1}	CH_4	21 CO_2 eq.		UNFCCC, 2014	
	N_2O	310 CO_2 eq.		UNFCCC, 2014	
Scenario input intensive					
Fertiliser – N		70 kg ha^{-1} yr^{-1}		Nonhebel (2002)	
Plantation lifetime		20 yr		Nonhebel (2002)	
Yield		10 t DM yr^{-1}		Nonhebel (2002) and Sannigrahi (2010)	
Scenario input extensive					
Plantation lifetime		∞			
Yield		2 t DM yr^{-1}			

4.4.1 Performance of the reference scenario

The ER and the EE of the reference scenario are respectively 9.8 and 81.4% when methane losses are aggregated with fossil input. When losses are left out the ER and EE are respectively, 13 and 83.7%. For every unit natural gas delivered 0.014 units CH_4 are emitted to the atmosphere and 0.1 units CH_4 are combusted. This results in the emission of 9.9 g CO_2 eq. · MJ^{-1} natural gas delivered to the grid. When combustion of the natural gas is included total emissions are 66 g

CO_2 eq. · MJ^{-1}. The energetic performance of the reference scenario is substantially higher than the simulated scenarios. The environmental advantage of a biogenic against an anthropogenic carbon source is not well represented in these figures.

4.4.2 Performance of the scenarios

The required quantities of SNG correspond to about 5.4 GW installed gasification capacity when producing continuous on a year-round basis (8760 hours). It is assumed that the installed gasification capacity is located near the port of Rotterdam.

When comparing the intensive scenarios 1 to 5 with the extensive scenario 0 it appears that the extensive scenario requires a factor 5 more land. The difference in performance of the scenarios 0 and 1 in which only drying and chipping are applied is determined by the fossil inputs into the intensive production system. The extensive system has the best energetic and environmental performance due to the absence of fossil inputs into the biomass production system. The difference in energy use and emissions between scenarios 0 and 1 with equal transport is very limited, these are, respectively 0.02 MJ · MJ^{-1} SNG and 3 g CO_2 eq. · MJ^{-1} SNG. The extensive scenario 0 shows small advantages compared to scenario 1, such as a better EE. The availability of land is a physical limitation, which is challenging to overcome, especially when large quantities are required. Therefore, this research continues with the analysis of intensive biomass production scenarios.

The results of the 6 simulations and the reference scenario are displayed in table 4-3. It gives an overview of the environmental impact and energetic performance of the different biomass to SNG chains. Biomass production contains the steps ploughing and preparation, crop protection, harvesting, fertilisation and loading. Transport energy consists of direct and indirect transport energy excluding forwarding, which is in the order of 0.5% of the total transport energy.

Scenario 2 underlines that transport is the determining factor in energy consumption and emissions. The GHG reduction potential more than triples, whilst the energy use decreases with a factor 2.6, all due to a change in transport mode. Scenario 3 shows that torrefaction has limited impact when inefficient transport is applied. The ER increases which is due to a decrease in fossil energy for transport. Despite the increase in demand for biomass when torrefaction is applied there is an energetic profit for transport. The differences in performance between scenario 2 and 4 are smaller. This underlines that the impact of torrefaction is limited when the transport mode is optimised. When comparing the difference between torrefaction and pelleting (scenario 4 and 5) it becomes clear that the EE and ER are in the same range despite the fact that torrefaction has no external inputs. The ER, however, decreases whilst the EE increases. The decrease in ER is caused by the increase in fossil input when pelleting is applied instead of torrefaction. The increase in EE is due to a decrease in biomass demand and an increase in fossil input. Despite the extra biomass that has to be transported due to torrefaction in scenario 4 it uses less energy than scenario 5 in which pelleting is applied instead of torrefaction.

Table 4-3: Environmental and energetic performance of the simulated scenarios.

Scenario		0	1	2	3	4	5	Reference	Unit
Energy Ratio		1.4	1.4	3.6	1.6	3.7	3.3	9.8	-
Energy Efficiency		20.6	18.7	50.6	24.2	48.6	49.9	81.4	%
Land requirements		0.36	0.07	0.07	0.07	0.07	0.07		$m^2\ MJ_{SNG}^{-1}$
Installed capacity		5.4	5.4	5.4	5.4	5.4	5.4		GW
Biomass production	Share of total	0.01	0.03	0.04	0.04	0.04	0.03		$MJ_{Fossil}\ MJ_{SNG}^{-1}$
Transport energy	Share of total	0.64	0.64	0.18	0.54	0.17	0.17		$MJ_{Fossil}\ MJ_{SNG}^{-1}$
Energy use	Direct	0.56	0.57	0.22	0.49	0.22	0.25	0.1	
	Indirect	0.14	0.16	0.06	0.14	0.06	0.05		$MJ_{Fossil}\ MJ_{SNG}^{-1}$
	Total	0.71	0.73	0.28	0.64	0.27	0.31	0.1	
CO_2 emissions	Direct	41	43	18	38	17	37	56	
	Indirect	8	9	3	8	3	3	10	g CO_2 eq.
	Total	49	52	21	46	20	40	66	MJ_{SNG}^{-1}
GHG reduction potential		24.7	20.3	68.5	30.5	69.1	39.2		%

Table 4-4: The environmental and energetic performance with 5% more efficient transport.

Scenario	0	1	2	3	4	5	Unit
Energy Ratio	1.4 (4.8%)	1.4 (4.6%)	3.6 (3.4%)	1.6 (4.4%)	3.7 (3.3%)	3.3 (2.9%)	-
Energy Efficiency	20.6 (10.9%)	18.7 (12%)	50.6 (1.3%)	24.2 (7.4%)	48.6 (1.2%)	49.9 (1.2%)	%
CO_2 emissions Direct	41 (-4.5%)	43 (-	18 (-	38 (-	17 (-	37 (-	g CO_2 eq. MJ SNG^{-1}
Energy use Direct	0.56 (-4.5%)	0.57 (-	0.22 (-	0.49 (-	0.22 (-	0.25 (-	MJ_{Fossil} MJ SNG^{-1}
GHG reduction potential	24.7 (28.1)	20.3 (23.8)	68.5 (69.5)	30.5 (33.3)	69.1 (70)	39.2 (40.1)	%

4.4.3 Sensitivity analysis

The largest energetic impact on the system is from transport and therefore the effect of a decrease of 5% in direct energy use for transport on the system is shown in table 4-4 assuming that transport becomes more efficient in the future.

Table 4-4 shows the increase or decrease of the ER, EE, carbon emissions and energy use between brackets when transport is 5% more efficient. The values for the GHG reduction potential are the actual values. The effect on the GHG reduction potential varies between 0.9% and 3.4%. This emphasises that the best performing scenarios are the least affected and a reduction in transport distance is required to significantly increase the biomass to SNG chain.

4.4.4 Energetic feasibility of torrefaction and pelleting

When the extra fossil input for pelleting, or the losses in biomass due to torrefaction, are larger than the gains from more efficient transport, it is energetically unfeasible to apply pretreatment steps, such as torrefaction and pelleting. Therefore, there is a break-even distance for transport in which the energetic performance of a biomass supply chain in- or excluding torrefaction or pelleting is the same. The energetic feasibility of these pretreatment steps is therefore dependent on the applied transport type and the transport distance.

The gasification process does not require a specific type of pretreatment in order to function. The only physical limitation is the size of the biomass particles injected into the reactor. Pretreatment does have a positive effect on the conversion efficiency of the gasification process. Furthermore, pretreatment decreases the energy use for transport. However, when the energy input or the energy losses due to pretreatment are larger than the reduction in transportation energy, the application of pretreatment is energetically unfeasible. Therefore, it is of interest to determine the break-even distances for transport in order to find the energetic feasibility of the whole biomass supply chain.

Table 4-2 shows the applied energy use for different transport types, which was used to develop figure 4-3. Figure 4-3 shows the break-even distances for the two transport modes applied in this research. Calculations for figure 4-3 have been done for the combination of indirect and direct energy per transport mode whilst assuming the net process efficiencies for torrefaction and pelleting to respectively be, 92% and 84% (Uslu et al., 2008). The error bars show the results when the energy densities from Uslu et al. (2008) are applied for torrefaction (20.4 $MJ \cdot kg^{-1}$) and pelleting (17.7 $MJ \cdot kg^{-1}$) instead of the calculated energy densities which are 14.3 $MJ \cdot kg^{-1}$ for dried biomass, 18.8 $\cdot$ MJ kg^{-1} for torrefied biomass and 15.9 $MJ \cdot kg^{-1}$ for pellets. Break-even distances are in 1000 km.

Figure 4-3 clearly illustrates why scenario 3 has a better performance than scenario 1. The transport distance in both scenarios is 3000 km by truck which is above the break-even distance for torrefaction. Based on figure 4-3, scenario 4 should have had a better performance than scenario 2, since the transported distance of 2500 km is far below the break-even distance for transport by barge. This is rescinded by the 500 km truck transport causing the scenarios to have a similar performance. Pelleting is energetically unfeasible, since both break-even distances for transport by short sea barge and truck are far above the realistic transport distances within Europe.

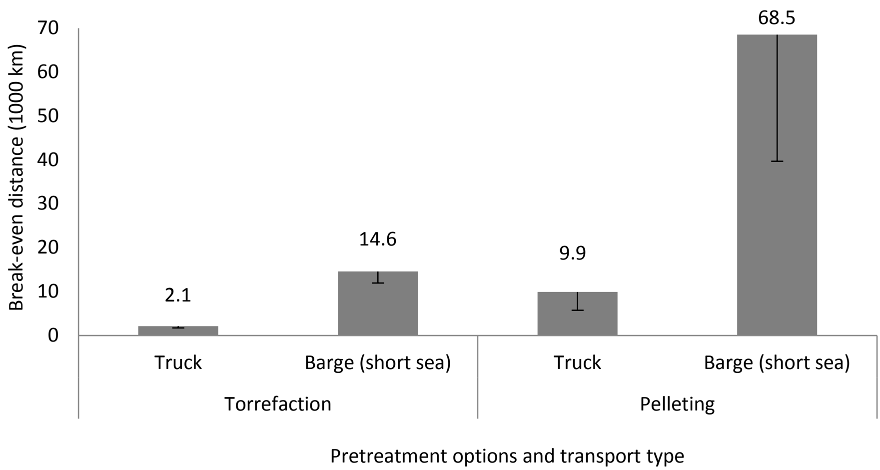

Figure 4-3: Break-even transport distances for torrefaction and pelleting by truck and short sea barge.

CHAPTER 4: SNG SUPPLY CHAIN

4.5 Discussion

The EE and the ER of the reference scenario are significantly higher than the EE and ER of the simulated scenarios. When taking into account that the EU is on the verge of a substantial energy system transition, it can be argued that a biogenic carbon source has clear advantages over an anthropogenic carbon source. Besides the GHG reduction potential of biomass for energetic purposes, this might be a reason to apply SNG at the cost of natural gas despite its smaller energetic performance.

Choosing an intensive system over an extensive system is accompanied with some insecure aspects. When large quantities of biomass are required an intensive system has logistic advantages, due to the need for less transport. Transport has the largest influence on the overall system performance. When taking the large quantities of biomass into account that are necessary to fulfil a rather small SNG demand it is justifiable to use an intensive system. Hence, when the required area is larger, the average forwarding distance will also increase. Besides this, the energy input for harvesting is expected to be higher per mass unit of harvested material. The environmental performance is determined by land requirements and CO_2 emissions. Emissions caused by ILUC are not taken into account. Scenarios one to five are expected to perform worse when ILUC is taken into account. When taking a worst case scenario (i.e. converted fens in Europe) emissions due to drainage might be in the order of 290 – 3230 g CO_2 eq. · m^{-2} yr^{-1} (Lamers et al., 2015). When comparing these values to scenario 4 with the largest GHG reduction potential it appears that emissions caused by ILUC are roughly 1 to 12 times higher. When emissions increase with a factor 4 due to ILUC the performance is even worse than the fossil reference scenario.

The estimated break-even distances and thus, the energetic feasibility of torrefaction within the European boundaries might vary when natural degradation of chipped biomass is taken into account.

The available forests in the EU are limited. Asikainen et al. (2008) estimate the amount of energy from forests (extensive systems) that can be harvested technically and sustainably in the EU27 to be in the order of 36 Mtoe · yr^{-1}. This is 24% of the theoretical potential and 9% of the primary energy demand in the EU for natural gas. The demand of 4.04 Mtoe · yr^{-1} (1% of the European natural gas consumption) would therefore require 5.8 Mtoe · yr^{-1} of raw biomass corresponding to 16% of the annual available biomass. This underlines that biomass from extensive systems has less potential to foresee in the desired quantities. Overall it becomes clear that replacing significant quantities of natural gas in the EU with SNG seems unfeasible when an extensive production system is used. In the most optimistic scenario 20% of the natural gas consumption could be replaced from extensive production systems, assuming that the annual increment rate can be harvested. In practice this value will be no more than 5% of the total natural gas demand. When looking at the intensive production system 1.4% of the arable land currently in use is required. Even when both production systems are combined, the EU cannot replace its natural gas consumption with SNG from indigenous biomass. Furthermore, replacing only 1% already has a substantial logistical impact. To illustrate this, the quantities transported correspond to 5% of the EUs current food flow.

Torrefaction or pelleting should be done when the desired conversion process needs a certain type of feedstock quality. This can relate to consistent feedstock quality in order to stabilise the conversion process, to avoid biological degradation, but also to grindability of torrefied biomass for use in coal-fired power plants. When the applied pretreatment is necessary, based on previous arguments, than it should be done as close to the harvest location as possible.

4.6 Conclusion

This study shows that the analysed biomass supply chains cannot compete with the conventional reference scenario when looking at the energetic performance and land use. The ER and EE of the reference scenario are, respectively a factor 2.6 and 1.6 higher than the best performing biomass supply chain. The reduction in GHG emissions is between 20% and 69% at the cost of respectively, 1.2 and 1.3 Mha, which emphasises the importance of well-designed biomass supply chains.

Depending on the design of the biomass supply chain, the environmental and energetic performance can be quite divergent. This is emphasised by the intensive scenarios 4 and 5. Whilst the energetic performances are in the same range, the environmental performances (when using carbon emissions as an indicator) differ respectively a factor 2.2. This shows that torrefaction overall has a better performance than pelleting, despite the requirement of 8% more land.

Pretreatment, such as torrefaction and pelleting, does not contribute to the energetic and environmental performance of the biomass supply chain within the borders of the EU when transport is optimised. This is supported by the difference in performance of scenario 1 and 3 in which biomass transport is kept constant and torrefaction is added. Truck transport is not optimal and therefore the contribution of torrefaction is significant. When transport is optimised the advantage of torrefaction is gone.

Determining the optimal scenario in the context of long term sustainability is a challenge, since sustainability has three components: social, environmental and economic. The ER and EE only take energy into account and are therefore not representative to determine the sustainability of biomass supply chains. The intensive scenarios 2 and 4 are the best performing scenarios when looking at energy use and carbon emissions. This emphasises that transport is the determining factor in biomass supply chain design.

5

Green gas in the Dutch residential sector

Opportunities and barriers for biomass gasification for green gas in the Dutch residential sector.

Abstract

The Dutch residential sector is locked-in into natural gas for the supply of heat. The expected depletion of national reserves and induced earthquakes in the production area are reasons to aim to escape this lock-in. The Dutch government and key players in the natural gas sector have expressed large green gas ambitions. This paper explores the opportunities and barriers of biomass gasification for green gas production and application in the residential sector. The Technological Innovation Systems and Multi-Level Perspective were applied as sustainability transition frameworks, to explore the current technological state of biomass gasification and the developments in the residential sector. Four limitations were observed from a supply perspective: little financial space for demonstration plants, absence of technology specific policy, lagging market developments and insecurities related to biomass availability. On the demand side, clear barriers hampering change are observed, providing large opportunities for green gas. Key players in the natural gas regime take no substantial responsibility, despite their potential ability to contribute to overcoming systemic barriers**.** Therefore, this research concludes that the current green gas ambitions, set by the Dutch government, are not feasible and that the government may address this with technology specific policy, substantial research and development subsidies and funding.

Keywords

Biomass gasification, Green gas, Residential sector, Multi-Level Perspective on sustainability transition, Technological Innovation Systems.

Chapter information	
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5.1 Introduction

The necessity for a transition of the energy system is determined by a number of factors relevant on different geographical scales. On a European scale there are three main policy objectives; mitigation of climate change, security of energy supply and economic competitiveness (i.e. affordable energy prices) (Keppler, 2007; European Commission, 2014b). These objectives have trickled down to the individual member states, who all have their individual challenges to fulfil such objectives, related to the design of their specific energy systems. The different targets for the share of renewable sources for the individual member states in Annex I of the Renewable Energy Directive (RED) (European Commission, 2009) not only emphasise the different starting points for the mitigation of climate change of the member states, but also implicitly take into account the individual challenges from the member states. On a national scale, the design of the energy system of the Netherlands is exceptional, due to the historic high share of natural gas in the energy mix. This was 47% in 2000 and 38% in 2015 (National Energy Outlook Summary, 2016). The discovery of the Groningen field in the northeast of the Netherlands in the 1960s (Levinsky and van Rij, 2011) has led to a large national dependency on low caloric natural gas. In addition, the historic quantities of natural gas in the Dutch sub-soil resulted in the Netherlands becoming an important supplier of natural gas in North-West Europe. However, the field is expected to become depleted in about two decades and the Dutch export position will change into a net dependency on natural gas imports. This awareness has led to the so-called Gas Roundabout strategy by the Dutch government in 2005, which aims to secure the supply of natural gas and to contribute to the continuity of the European natural gas supply (General Accounting Office, 2012). The dependency has led in particular to a lock-in of the Dutch residential sector, where 93% is connected to the low caloric natural gas grid for heating purposes (Schoots and Hammingh, 2015). The average consumption in a Dutch household is about 1500 $m^3 \cdot yr^{-1}$ (CBS, 2016c) for space heating, hot water supply and cooking, making the residential sector responsible for the consumption of about 11 billion cubic meters (bcm), which is almost half of the current annual production from the Groningen field. However, production from this field has led to over 1000 induced earthquakes causing damage to existing buildings and contributing to social turmoil (van der Voort and Vanclay, 2015).

Recently, the Dutch Petroleum Company (NAM) was forced by the Minister of Economic Affairs to reduce production from the Groningen field to 24 bcm or 760 $PJ \cdot yr^{-1}$ (Government of the Netherlands, 2016), as a response to induced earthquakes. During a transitional period towards a sustainable energy system, green gas supply can contribute to a further reduction of the Groningen field production levels; this may result in a decrease in the number and severity of the induced earthquakes (Muntendam-Bos and de Waal, 2013; Joustra et al., 2015). A large role for green gas is expected by the Dutch government and key players in the natural gas sector during the transitional period towards a sustainable heat supply system. The most recent agreement related to the supply of heat is the Heat Vision document. It suggests a tripling of renewable heat production is possible from 6.1 PJ to 18 PJ between 2013 and 2023 (Kamp, 2015). This renewable heat should originate from biogas combustion with combined heat and power (CHP) and green gas through biogas upgrading. The Dutch gas trade company GasTerra states that up to 3 bcm of green gas (or about 95 PJ) can be produced in 2030 (GasTerra, 2016). Such quantities require large scale production of green gas. In order to supply the expected quantities of green gas, gasification technology is thought to have large potential. Gasification can be used to convert basically all carbon containing compounds into gaseous products (Speight, 2015). Biomass gasification combined with a methanisation unit is an innovative developing technology, which can be used to produce a green gas suitable for injection into the existing gas grid.

The aforementioned factors, climate change, depletion of the low caloric natural gas field, induced earthquakes, a large national dependency on natural gas, and the residential sector being a captive customer, emphasise the need for a transition of the residential heat supply system in the Netherlands, in a short timeframe. In this article, the Dutch residential sector is regarded as a captive customer, since the rate of return of renewable heat supply technology is often too long, or the capital investments are too high for a large part of the population. Biomass gasification can potentially contribute to all these factors. Green gas produced through biomass gasification can positively contribute to climate change from a greenhouse gas perspective (Miedema et al., 2016). Furthermore, large quantities of green gas can potentially reduce the dependency on the Groningen field, contribute to reduced production levels from the Groningen field and with that possibly a reduced number of earthquakes.

Biomass gasification can serve as an incremental innovation, since it can stabilise the transition towards sustainable heat supply in the residential sector. Therefore, the aim of this research is to explore the opportunities and barriers of biomass gasification for green gas production and application in the Dutch residential sector.

5.2 Methodology and frameworks

The Multi-Level Perspective on sustainability transition (MLP) and the Technological Innovation System (TIS) are the frameworks that have dominated the literature concerning sustainability transition theory (Walrave and Raven, 2016). The TIS framework is applied here to explore the current technological state of biomass gasification and with that its technical possibilities to supply green gas.

The MLP is used to explore the position of key players in the natural gas sector and the position of the residential sector as captive customers. The captivity of the residential sector is addressed by exploring the absence or presence of six potential barriers, hampering diffusion of renewable energy technology, provided by Reddy and Painuly (2004). By including so-called socio-technical regimes and landscape pressures in this analysis, the TIS approach can be applied to explore transitions (Markard et al., 2015) and with that the potential role of biomass gasification and green gas, during the transition towards sustainable heat supply in the Dutch residential sector.

5.2.1 Sustainability transition frameworks

The TIS framework provides a check-list, based on a set of seven so-called system functions. According to Hekkert et al. (2007), the functions approach should be regarded as a process or history event analysis. This functions approach has been applied before by Suurs (2008) and Negro et al. (2008), on the topic of biomass gasification. These historic case studies aim to explain the failure of the diffusion of biomass gasification. They regard the absence of system functions as indicators for failure of the diffusion of biomass gasification. The functions approach is argued to be generic enough to explore varying TISs and find barriers (Bergek et al., 2008; Markard et al., 2015). Therefore, the TIS framework was applied for the analysis of the current technological state of development of biomass gasification. The system functions are listed in the first column of table 5-1 and were taken from Hekkert et al. (2007); the second column lists a number of relevant indicators taken from Hekkert et al. (2007) and Wieczorek and Hekkert (2012). These indicators were adjusted for the specific case of biomass gasification in order to find systemic barriers for biomass gasification and form a basis for some policy recommendations to overcome these barriers. The framework by Wieczorek and Hekkert (2012) is argued to be suitable for both policy makers and innovation scholars.

Table 5-1: TIS system functions and operationalised indicators applied in this research.

System Functions	Indicators
1 Entrepreneurial activities	Entrepreneurs experimenting with biomass gasification
	Varying feedstock
	Varying output
	Varying scales
	Specific research about technological performance
2 Knowledge development	Scientific theory and experiments
	Actors responsible for financial space
	Applied research projects
	National research and technology programs
	Pilot and demonstration plants
3 Knowledge diffusion	Partnerships
	Publicly available feasibility assessments
	Actors contributing to knowledge development
4 Guidance of the search	Policy documents, strategies and agreements
	Induced government activities
	Technology specific policy
	Green gas policy
	Technological expectations
	Policy documents from the natural gas regime
5 Market Formation	Market size
	Current and potential users
	Leading parties
	Institutional incentives/barriers
6 Resource mobilisation	Adequate public funding
	Adequate risk capital
	Actors with resources and capabilities
	Supportive networks for innovation
	Biomass supply and supply expectations
	Biomass prices
7 Counteracting resistance	Supportive bottom-up initiatives
	Legitimate investment decision

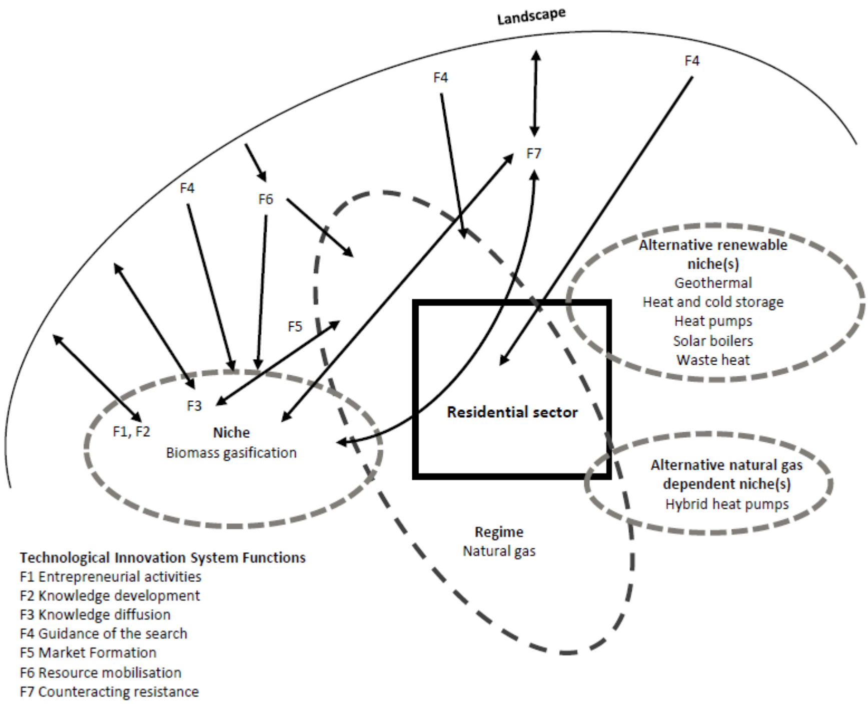
System functions were taken from Hekkert et al., (2007). Indicators were taken from Hekkert and Ossebaard (2010) and from an extensive list provided by Wieczorek and Hekkert (2012). Indicators were operationalised for this specific research when necessary.

The MLP on sustainability transitions is a qualitative framework, suitable for the analysis of long term transitions related to challenges such as resource depletion (Weber and Rohracher, 2012). It applies three levels of change (i.e. the landscape, regime and niche level), where respectively the dynamics between macro developments, existing configurations and developing technology can be explored. Geels (2011) defined the niche level as "[…] 'protected spaces', such as Research and Development (R&D) laboratories, subsidised demonstration projects, or small market niches where users […] are willing to support emerging innovations […]". The regime level was defined as "[…] the deep structural rules that coordinate and guide actor's perceptions and actions […]" within "[…] the alignment of existing technologies, regulations, user patterns, infrastructures and cultural discourses […]". The landscape was defined as "[…] the wider context, which influences niche and regime dynamics", which "[…] includes spatial structures […] political ideologies, societal values, beliefs, concerns, the media landscape and macro-economic trends" (Geels, 2011). General patterns in transitions are described by the interactions between these levels. The approach is graphically presented in figure 5-1. In this figure, biomass gasification is presented as a niche technology and explored with a TIS analysis.

5.2.2 Data collection

Empirical evidence was gathered by a number of semi-structured interviews and literature review by looking through scientific databases. Semi-structured interviews were conducted with key players, including representatives from a leading housing corporation (J. Leistra, Wold en Waard), municipality (B. de Boer, Municipality of Leeuwarden), province (H.J. Bouwers, Province of Friesland), energy supplier (M. van Son, NLDenergie), and of main companies in the natural gas sector involved in the trade (G. Martinus, GasTerra), infrastructure (W. de Groot, Gasunie), transmission (W. de Groot, GTS) and distribution (M. van Dam, Enexis) of natural gas. Additionally, policy from the European Union (EU), like the RED (European Commission, 2009) and the Energy Performance of Buildings Directive (EPBD) (European Commission, 2010), were analysed as landscape pressures. The national policy documents taken into account are the Energy Agreement on Sustainable Growth (SER, 2013) and the Heat Vision (Kamp, 2015). The future role of natural gas and with that the potential for green gas was estimated by extrapolating the ambitions formulated in current policy when it comes to increased energy efficiency and alternative technology in the residential sector until 2030. The expectations towards green gas in the natural gas sector were explored by combining the semi-structured interviews with annual reports from actors dominating the natural gas sector (between 2011 and 2016). The developments in the residential sector were explored by reports from housing corporations and scientific literature.

This article is structured as follows. The results and discussion section starts with possible green gas production routes, after which the TIS analysis for biomass gasification is presented. Subsequently, the change in energy performance and diffusion of renewable heat technology in the residential sector is explored. In addition, the natural gas regime is delineated on a sectoral basis. The discussion section is applied to address the methodological choice for such regime delineation and to present the observed opportunities and barriers. The concluding section combines the observed insights from the supply (biomass gasification technology) and demand side (residential sector) in combination with the expectations of the government and the natural gas regime.



5-1: Overview of the TIS functions for biomass gasification, including alternative niches for residential heat supply, the natural gas regime, the residential sector and the landscape level. The arrows indicate the dynamics between different levels and the TIS functions, single arrows indicate unilateral pressures, whereas double arrows indicate bilateral dynamics combined with the system functions from TIS. The residential sector is presented as a black box to emphasise its position as a captive customer within the natural gas regime. Figure 5-1 is based on Markard and Truffer (2008).

5.3 Results

5.3.1 Green gas production routes

In order to supply the envisioned quantities of green gas two technologies can be applied, that are biological or thermochemical. Currently, the largest part of biogas is produced through the biological route, with anaerobic digestion (AD) processes in the Netherlands. With AD about 13 PJ of biogas was produced, of which 2.6 PJ was converted into green gas and injected into the grid in 2016 (CBS, 2017a). Figure 5-2 gives an overview of the green gas production routes for AD and gasification, including the production of alternative energy carriers. This research focuses on the gasification route emphasised by the dashed square in figure 5-2. AD is included in the figure, since it is the only option for green gas production currently installed in the Netherlands on a substantial scale. Given that production of biogas is 13 PJ (CBS, 2017a), roughly a doubling of installed capacity would be required when an overall efficiency of 75% is assumed for biogas upgrading to green gas (Bekkering et al., 2010), if the target of 18 PJ is to be met in 2023. In addition, almost half of the biogas is produced trough co-digestion of manure at a farm level (CBS, 2017a) in rural areas. All this biogas is combusted with CHP, with the main purpose of electricity production and supply of the required process heat (CBS, 2017a). Adjustments of these plants, with an upgrading step would be required in order to produce a green gas. However, the produced quantities are limited by demand, since these farms are connected to the low pressure distribution grid. Continuous production may result in supply problems, because the low pressure distribution grid has limited injection capacity (Bekkering et al., 2015), since it is a unidirectional grid. This causes local limitations, especially in summer when there is low demand (Bekkering et al. (2015); personal communications with M. van Dam, Enexis on 10-03-2015 and H.J. Bouwers, Provinsje Fryslân on 20-03-15). The high pressure transmission grid is therefore more suitable for injection of green gas (personal communication with H.J. Bouwers, Provinsje Fryslân on 20-03-15). In addition, linepack can be applied as a source of flexibility when there are imbalances between injection and extraction (Schipperus and Mulder, 2015). Producing substantial amounts of green gas in 2030 is therefore not expected from AD. Biomass gasification should result in centralised production of large quantities of green gas and therefore the high pressure transmission grid can be used for injection, overcoming the capacity issues.

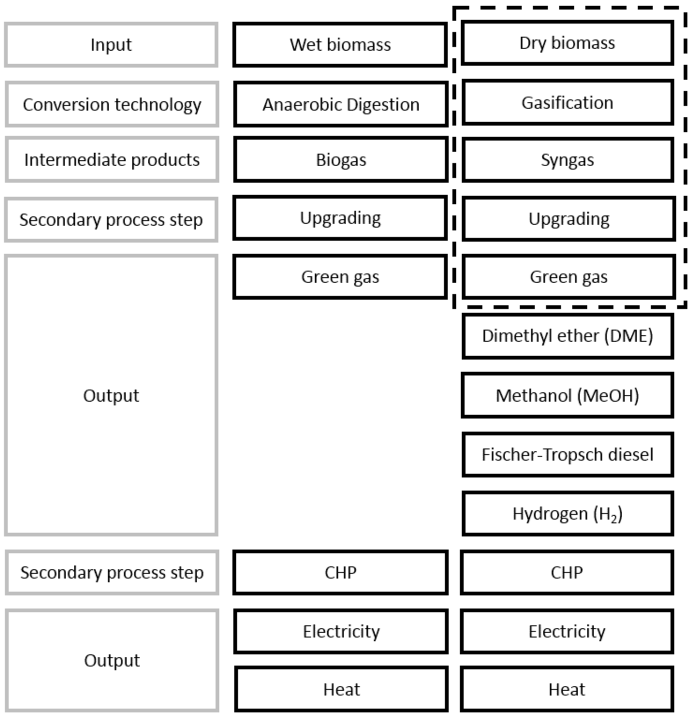


Figure 5-2: Overview of the possible green gas production routes from AD and gasification including alternative output fuels.

5.3.2 TIS description of biomass gasification

Contrary to AD, biomass gasification technology for green gas production is not implemented on a large scale. Coal gasification for the production of synthetic natural gas (SNG) is a proven technology (e.g. Dakota Coal Gasification Company, n.d.); biomass gasification is still subject to technological challenges which need to be resolved. Therefore, this paper continues with a systemic approach to explore the factors that form barriers for diffusion of biomass gasification.

A variety of companies, research institutes, universities and collaborations between these three have led to a number of pilot and demonstration plants (Bacovsky et al., 2013; Ridjan et al., 2013; Karltorp, 2016). There is a variety in biobased feedstock, from woody lignocellulosic biomass, gaseous and liquid fuels (e.g. syngas and black liquor) and waste (refuse derived fuel). The output products vary between electricity, heat and different liquid and gaseous fuels. The gaseous fuels are biogas, syngas and SNG. SNG is a green gas suitable for injection into the natural gas grid. Liquid fuels are dimethyl ether and Fischer-Tropsch diesel, which are renewable transport fuels. Given the variety of possible output products for biomass gasification (figure 5-2) that are being researched, selection of an optimal design for the biomass gasification technology has not taken place. A number of biomass gasification initiatives can be identified in Europe. An overview of biomass gasification projects in Sweden and Denmark is provided by Ridjan et al. (2013). Of the 19 identified projects only one demonstration plant was designed with the purpose to produce green gas. In addition, Bacovsky et al. (2013) identified 23 thermochemical conversion initiatives on a global scale. Two additional initiatives were found that produce green gas in the Netherlands. Furthermore, Karltorp (2016) gives an overview of 14 biomass gasification projects in Europe, with five additional initiatives, of which one semi-commercial plant aimed to produce green gas. This semi-commercial plant was however, put on hold (Karltorp, 2016). The emphasis on green gas production lies therefore in the Netherlands. The latter plant mentioned by Bacovsky et al. (2013) and Karltorp (2016) is, however, still in its planning stage. The first Dutch plant is a 800 kW pilot installation by ECN, which had successful trials (van der Meijden et al., 2008; 2010), and they aimed to increase the scale to about 10 MW, since 2010 (van der Meijden et al., 2010). Currently, the plans for this demonstration plant are renewed by a collaboration between the province, municipality, and various actors being part of the biomass gasification niche and the key players in the natural gas sector (NHN, 2016; Energyvalley, 2016) and construction is being planned for 2018 (ECN, 2017). The Dutch province of Noord Holland has agreed to invest about €1 million in the development of a biomass expertise centre and €0.5 million in the development of a demonstration plant for biomass gasification technology as developed by ECN (NHN, 2016). Total cost is in the order of €23 million; this collaboration has agreed to foresee in the remaining €21.5 million. Other initiatives in the Netherlands related to biomass gasification are from BioMCN (biofuel production), Synvalor (engineering consultant), Torrgas (small scale syngas production), Heveskes (conversion technology), HVC Alkmaar (waste treatment), HoSt (engineering) and ECN (research institute) (van der Drift, 2013). These are currently quite small initiatives when looking at scales of production (aside from BioMCN).

The output of theoretical scientific knowledge related to biomass gasification increased on average with 20% per year since 2000 when looking at results from Web of Science when using biomass gasification as keyword. Furthermore, the Netherlands had the EDGaR program, in which research addressing biomass gasification for green gas also had a substantial role between 2010 and 2015 (EDGaR, n.d.). A follow-up program was not realised. Experimental knowledge is developed through a number of pilot and demonstration plants. However, increasing the scale from a pilot plant to a demonstration plant or from demonstration to a commercial plant proves difficult. Karltorp (2016) mentions the example in Finland, where a 12 MW pilot plant had successful trials, but still stopped experiments afterwards. In addition, Hellsmark and Jacobsson (2012) observe a more general trend where the shift from demonstration plants to a commercial scale hampers. In the Netherlands this story is similar, since the aim to increase the scale of the 800 kW pilot plant to a 10 MW demonstration plant exists for eight years already. In addition, further development to early commercialisation and full scale commercial plants is a lengthy process. Furthermore, Hellsmark and Jacobsson (2012) argue that it takes at least three years after the construction of a demonstration plant is finished, before the performance is good enough to find investors for a pre-commercial plant. Further upscaling, permits for construction and construction itself, of a full scale commercial plant, that can contribute to the transition in the Dutch residential sector, is a process that will take more than a decade at best.

Technology specific policy could contribute to the aforementioned required developments, but the Dutch government has only put in place an operating grant for promotion of renewable energy, called SDE$^+$, which provides the opportunity for investors to receive financial compensation for the production of renewable energy for a certain period. This should accelerate the implementation of renewable energy technology. The high initial cost of such a large plant is, however, difficult to overcome and an operating grant is therefore not useful. Despite the absence of technology specific policy, lower governments play a facilitating role by supporting local initiatives and bringing entrepreneurs together (SER, 2013; personal communications with H.J. Bouwers, Provinsje Fryslân on 20-03-15 and B. de Boer, Municipality of Leeuwarden 05-11-2014). The current planning of the 10 MW demonstration plant by ECN, Gasunie, Dahlman and HVC in Alkmaar is an example of a collaboration and the facilitating role of lower governments.

Furthermore, a market for green gas should be present. This could be the residential sector, but this is highly dependent on future natural gas and green gas prices, and the cost for alternative renewable technology to supply heat. Thus, besides the technical development, the development of both the natural and green gas prices are of importance. Depending on the feedstock cost, the green gas cost will be €14 to €24 GJ^{-1}, which is currently twice the price of natural gas (van der Drift, 2015). However, natural gas prices are expected to rise (€11 to €14 GJ^{-1} in 2030) and therefore green gas has possibilities to become competitive in the coming decades. A low feedstock price can be attained by the application of waste instead of biomass as feedstock. Future biomass prices are insecure, given the expected global availability of 33 to 1135 EJ a^{-1} in 2050 (Hoogwijk et al., 2003). Besides that, biomass for energy purposes is subsidy-driven, since there is a direct relation between biomass co-combustion in coal-fired power plants and national subsidy structures in the Netherlands (CBS, 2013). The most recent estimates for demand and supply of biomass within the Dutch bioeconomy show that demand exceeds domestic supply with at least a factor two and possibly a factor nine in 2030 (Commissie Corbey, 2014). This is emphasised by the example of a relatively small scale initiative like the biomass incineration plant from Eneco (49.9 MW_e), that requires waste wood, which is already imported from neighbouring countries (RVO, n.d.; personal communication with J. de Haas, CEO at Eneco on 09-12-2015). When green gas production is combined with higher value renewable products, the additional profits can be applied to reduce the cost for green gas production. Co-production of value-added chemicals may result in a cost reduction of €4.5 GJ^{-1} (van der Drift, 2015). This would require flexible production of which the importance, when it comes to input and output products, is emphasised in literature (Faaij, 2006; Kirkels and Verbong, 2011; Ahrenfeldt et al., 2013; Heidenreich and Foscolo, 2015).

Table 5-2 summarises the results of this TIS analysis, where the systemic barriers are also included. The TIS analysis shows that the development of biomass gasification technology for green gas in the Netherlands is still in the formative phase. The larger part of the systemic barriers are institutional and due to lacking financial, or knowledge infrastructure. The required network interactions between the players in the biomass gasification TIS and key players in the natural gas sector, have led to a collaboration that is aiming to continue with the currently planned demonstration plant in the Netherlands. Further technological development and diffusion of biomass gasification is limited by four factors. First is the inability of the involved actors to increase the scale to demonstration and subsequent pre-commercial or full scale commercial plants. In the Netherlands, this inability is the result of the absence of financial infrastructure for investments, and not because of unsuccessful testing. High capital investments are required; with insecure profits, this results in large investment risks. Expectations for green gas are, however, large; this holds for key players in the natural gas sector, but also for Dutch politics and parties involved in the development of Dutch energy strategies. Second is the institutional barrier, that involves the absence of technology specific policy. Lower levels of the Dutch government aim to facilitate initiatives in line with the existing strategies and the key players in the natural gas sector, collaborate with the technology developers. Key players contribute to the direction of the technological development of biomass gasification, but the current quantity of the investments does not guarantee successful diffusion of biomass gasification to foresee in the desired quantities of green gas in 2030. Third is the absence of a substantial market. A market share of 5% for green gas, as envisioned by the Dutch government in 2023, which is a requirement for successful diffusion of a technology (Geels and Schot, 2007) is not guaranteed. Fourth are limitations related to knowledge and financial infrastructure, which involve the insecurity related to future biomass prices and availability as feedstock for energy purposes.

Table 5-2: Overview of the present (+) and absent (-) system functions and the systemic barriers.

System Functions	Indicator	Present	Remark	Systemic Barrier
1 Entrepreneurial activities	Entrepreneurs experimenting with biomass gasification	+	A variety of institutes in the EU and multiple small initiatives/companies in the NLs not all related to green gas	
	Varying feedstock	+	Biomass and waste in the EU, biomass in the NLs	
	Varying output	+	Electricity; renewable gases; liquid fuels; building blocks for chemical industry in the EU, green gas in the NLs	
	Varying scales	+	500kW to 160MW in the EU, 800 kW for green gas is present in the NLs	
	Specific research about technological performance	+	A variety of institutes in Europe, ECN in the NLs	
2 Knowledge development	Scientific theory and experiments	+	Clear increase in theoretical scientific output since 2000; gasification was part of the Energy Delta Gas Research programme	
	Actors responsible for financial space	+/-	Financing is difficult, there are delays; Dutch national subsidies are focused on production (SDE$^+$) not on construction and development	Institutional and financial infrastructure
	Applied research projects	+/-	Lower level governments facilitate niche and regime initiatives	Institutional and financial infrastructure

	National research and technology programs	-	EDGaR was finished in 2016, no follow-up programme	Financial and physical infrastructure
	Pilot and demonstration plants	+/-	Financing is difficult; there are delays; construction of 10 MW demonstration plant is planned in the NLs since 2010	Institutional and financial infrastructure
3 Knowledge diffusion	Partnerships	+	Collaboration between niche players and the natural gas regime	
	Publicly available feasibility assessments	+	Green gas production cost, technological assessments of biomass gasification	
	Actors contributing to knowledge development	+	Both on niche level and natural gas regime	
4 Guidance of the search	Policy documents, strategies and agreements	+/-	Energy Agreement and Heat vision; implementation is behind schedule	Institutional
	Induced government activities	+/-	Facilitating role for lower governments; financial means are too small	Institutional and financial infrastructure
	Technology specific policy	-	No specific support schemes for biomass gasification	Institutional
	Green gas policy	+/-	Subsidy schemes are present; high green gas expectations; aim is 18 PJ in 2023, no clear role for biomass gasification	Institutional, interactions and actors
	Technological expectations	+/-	No clear view on the future role of biomass gasification	Knowledge infrastructure, network interactions
	Policy documents from the natural gas regime	+	Annual reports of players in the natural gas regime show openness towards green gas	
5 Market Formation	Market size	+/-	Currently a niche market, potentially large in the residential sector	Institutional
	Current and potential users	-	Potential in the residential sector	Institutional
	Leading parties	+	Players within the natural gas regime	
	Institutional incentives/barriers	-	Upscaling of technology is difficult due to financial means	Financial infrastructure
6 Resource mobilisation	Adequate public funding	-	ISDE subsidy is only available for proven technologies	Institutional
	Adequate risk capital	+/-	Over €20 million from public and private parties, not enough for upscaling	Institutional, network interactions

	Contributions from actors with resources and capabilities	+	10 MW demonstration plant in Alkmaar	
	Supportive networks for innovation	+	United in a consortium of niche an regime players	
	Biomass supply and supply expectations	-	Small projects already require imports	Knowledge infrastructure
	Biomass prices	-	Unpredictable	Financial and knowledge infrastructure
7 Counteracting resistance	Supportive bottom-up initiatives	-	Small energy corporations have little access to green gas	Institutional
	Legitimate investment decision	-	Investment risk is high, due to uncertain outcomes	Knowledge infrastructure

5.3.3 Implementation in the residential sector

Now that the barriers for green gas on the supply side are identified, this section explores the developments in the residential sector in order to find the potential for green gas on the demand side. The residential sector is regarded as a captive customer within the natural gas sector. In order to get insights in the potential for green gas, this section is used to indicate the existing barriers towards implementation of improved energy performance measures and alternative heat technology, in the residential sector. Six potential barriers limiting the diffusion of renewable energy technology, namely awareness and information, economic and financial constraints, technical risks, institutional and regulatory barriers, market barriers and behaviour, were provided by Reddy and Painuly (2004). The actors influencing change in the residential sector are divided in three groups. These are the owners in the private sector, the housing corporations and its tenants. The EPBD (European Commission, 2010) is the overarching European policy that focuses on the energy performance of the built environment and with that the residential sector. It aims to have new houses built that, on average, produce similar quantities of energy as they consume. The EPBD introduced the energy performance certificates for buildings, ranging from A+++, being the best to G, being the worst performer. A minimum of a certificate C is required in the private sector and a minimum of certificate B for property of housing corporations, in 2020 (Ministry of BZK, 2012).

About one-third of the residential sector is managed by housing corporations (Visscher et al., 2016; Guerra-Santin et al., 2017). Although Schilder et al. (2016) argue that the financial space for housing corporations is large enough, the main goal of a B certificate for this sector (Ministry of BZK, 2012) is not expected to be met in 2020 (Schoots et al., 2016; Visscher et al., 2016). In addition, AEDES (the national organisation that promotes the interest of almost all housing corporations) (AEDES, n.d.), argues in their annual reports that the financial space for investments of the housing corporations is not as strong as thought (AEDES, 2015; 2016). Proposed adjustments to the Heat Law are expected to indirectly force housing corporations to switch from collective heat supply to individual natural gas boilers (AEDES, 2018). Collective heat contributed for 5,5% to heat supply in the residential sector in 2016 (CBS, 2017b). Collective heat supply is mainly driven by natural gas and is assumed to increase up to one-third of the total supply in 2030 (Kamp, 2015). Visscher et al. (2016) argue that convincing tenants to participate in energy saving measures, that result in an increase in rent, is challenging. In addition, the energy certificates A and B underestimate the actual natural gas use, whereas the certificates E, F and G overestimate the actual natural gas use (Majcen et al., 2013; Visscher et al., 2016). An increased cost for rent due to energy saving measures, combined with lower energy cost is therefore no guarantee that tenants will end up with lower monthly cost. In addition, van Middelkoop (2014) argues that this risk of increased cost is especially relevant for tenants who already use little energy for heat, for economic reasons. Furthermore, a large part of tenants was found to have little interest in the energy performance of their homes (Vringer et al., 2016). Besides that, van Middelkoop et al. (2017) emphasise that investments in the private sector in energy performance of buildings offers economic benefits. Despite this, private owners are not easily convinced to improve the energy performance of their households (van Middelkoop et al., 2017). In addition, residents' behaviour and heating technology are two important factors in the total energy consumption in the Dutch residential sector (Guerra-Santin and Itard, 2010; Brounen et al., 2012; van Middelkoop et al., 2017). Van Middelkoop et al. (2017) recognise the importance of heating behaviour, but also argue that this importance is not visible in Dutch policy. Brounen et al. (2012) mention that efficiency increases may be annihilated, due to the behavioural aspects related to an ageing Dutch population. In addition, smart-metering technology may contribute to awareness within households, but does not guarantee behavioural change. Currently, the effect of smart-meters has offered no more than 1% reduction in heat demand (Vringer and Dassen, 2016). When it comes to heating technology, Hekkenberg and Verdonk, (2014) mention that with current policy 9% of the high efficiency boilers in the residential sector will be replaced in 2030. The expected substitute technologies are hybrid boilers, which still have a natural gas dependency, and electric heat pumps. When considering the government's heat specific policy (Kamp, 2015) it aims to avoid increasing dependency on politically instable regions by diversifying the heat supply in the Netherlands. They see potential for a variety of technologies, like heat and cold storage, geothermal heat, solar boilers, biomass and (hybrid) heat pumps. Collective heat supply could be up to a third of the total heat demand in 2030. In regions where heat supply remains dependent on gas (i.e. in areas with a low population density), the goal is to replace this to a large extent with renewable gases. The contribution of green gas to heat supply is expected to be between 6.1 and 18 PJ in 2023 (Kamp, 2013), of which the latter is 5% of the current natural gas consumption in the Dutch residential sector. Schoots and Hammingh (2015) argue that the largest challenges, when it comes to the implementation of this policy, are the absence of a market model and infrastructure. The absence of physical infrastructure does not hold for green gas, since green gas can be distributed via existing grids. Table 5-3 summarises the existing barriers hampering change in the residential sector.

Figure 5-3 is used to determine the minimum market share for natural gas in the residential sector in 2030, by extrapolating the government's policy targets for 2023 (Kamp, 2015) until 2030. The ambition to increase the energy performance of 300,000 existing buildings with two certificate steps until 2020 (SER, 2013) is taken into account, by assuming a reduction in heat demand due to improved insulation, of 1.4% and 1% respectively, between 2010 and 2020 and 2020 to 2030 (based on Schoots et al., 2016). Starting points for geothermal, heat and cold storage, heat pumps, solar boilers, waste heat and green gas in 2013 were taken from Kamp (2015). For collective heat supply 8 PJ was used as a starting point in 2013, which is roughly a third of the available collective heat (Menkveld et al., 2015), but results in an overestimation when compared to Schoots et al. (2017).

Table 5-3: Barriers affecting change in the residential sector.

Barriers	Housing corporations	Tenants	Private owners
Lack of awareness and information	Difficult to convince tenants to accept increased rent prices	Large part shows little interest in energy performance	Despite economic benefits owners are not easily convinced to implement technology
Economic and financial constraints	Limited financial space for investments	Insecure net effect of increased rent and decreased energy cost	Captive customers
Technical risks	Absent infrastructure for centralised renewable heat supply besides green gas		Absent infrastructure for centralised renewable heat supply besides green gas
Institutional and regulatory barriers	Heat Law may provide adverse incentives Policy agreements are not mandatory	Policy agreements are not mandatory	Policy is not mandatory
Market barriers	Absent market model		Absent market model
Behaviour	Positive attitude towards change	Smart meters have little effect on behaviour	Smart meters have little effect on behaviour

In figure 5-3 the total heat supplied with natural gas is half of the demand, with the assumption that collective heat is based on natural gas, resulting in a demand around 5 bcm from the Groningen field in 2030. In addition, the government's heat policy is not very specific on the sector where renewable heat should be applied. All renewable heat that is not specifically allocated to a sector in the existing policy is assigned to the residential sector, which means that the demand for natural gas in the residential sector in 2030 is an underestimation. The captivity of the residential sector in the natural gas regime becomes smaller, but remains substantial. The market share for natural gas in the residential sector remains large and with that the potential for green gas as a means to foresee in renewable heat.

In summary, the efficiency targets are not likely to be met in 2020 (Vringer et al., 2016), and the expected share of installed renewable heat technology in the residential sector is low in 2030 (Hekkenberg and Verdonk, 2014). Given that the required infrastructure for distribution and consumption of natural gas is present in the Netherlands, and landscape factors, such as the coming depletion of the Groningen field, the resulting import dependency and the continued captivity of the Dutch residential sector, a renewable alternative for natural gas, such as green gas, has large potential for renewable heat supply in the residential sector.

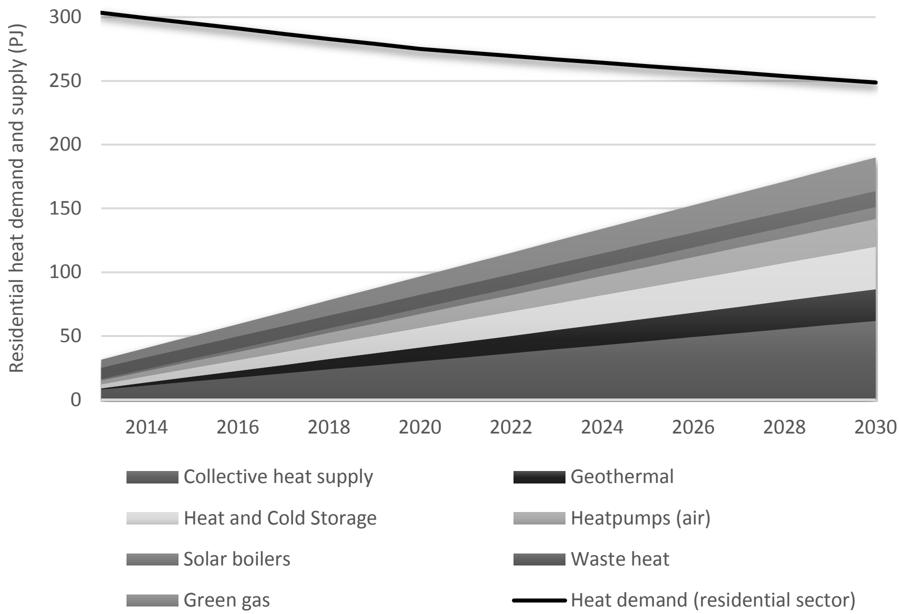


Figure 5-3: Residential heat demand for space heating, hot water and cooking. The demand for cooking is marginal (i.e. roughly 7.5 PJ, based on 32 $m^3 \cdot household^{-1}$ (RVO, 2016)); the demand for hot water is about 63 PJ based on an average showering time of 8.12 minutes (RVO, 2016), a flow rate of 10 litre $\cdot$ min^{-1} and a temperature difference of 30 Kelvin. The remainder is required for space heating. Data are in petajoule (10^{15} joule).

5.3.4 The natural gas regime

The previous sections showed that biomass gasification technology cannot supply large quantities of green gas in the short term, whilst meanwhile a transition in the residential sector is lagging behind. In this section the natural gas regime is delineated to explore their perceptions towards green gas and their potential ability to contribute to overcoming systemic barriers**.** Here, the natural gas regime is defined as: the parties involved in the supply chain from natural gas production from the Groningen field, including end-use in the residential regime. The residential sector is a part of the natural gas regime, as shown in figure 5-1. Key parties are the joint venture between Royal Dutch Shell and ExxonMobil, known as the Nederlandse Aardolie Maatschappij (NAM). The NAM is responsible for the natural gas production in the Groningen field. The produced natural gas by the NAM is purchased by GasTerra, the Dutch gas trading company. Their mission is to maximise the Dutch value of natural gas reserves in the Netherlands (GasTerra, 2016). GasTerra is owned for 25% by Shell, 25% by ExxonMobil, 40% by Energiebeheer Nederland (EBN) and 10% by the Ministry of Economics. GasTerra has the responsibility to maximise the value of the Dutch natural gas reserves and thus serves as a natural gas trade company. GasTerra expected 0.3 bcm of green gas to be produced in 2014 and an increase to 3 bcm (95 PJ) in 2030, already in 2011 (GasTerra, 2011). In this same year, GasTerra started with green gas contracts (GasTerra, 2011). In practice, GasTerra purchased about 60 million cubic meters of green gas in 2016 (GasTerra, 2016), which is about 0.5% of the natural gas consumed in the Dutch residential sector (CBS, 2016c). In 2016, GasTerra stated that energy should be saved and renewable energy, with an emphasis on green gas, should be promoted (GasTerra, 2016). Maatschap Groningen (Partnership Groningen) consists of NAM for 60% and EBN for 40%. This partnership was constructed in order to give the Dutch government the possibility to participate in the development of the Groningen field; the consequence was that the NAM became the operator for the concession and responsible for the risk. Furthermore, the NAM is obliged to sell all the produced natural gas from the Groningen field to GasTerra (van Gastel et al., 2014). EBN, which is fully owned by the Dutch state is responsible for participating in, and facilitating the, exploration and production, trade, transport and storage of oil and gas. Gasunie is fully owned by the Dutch government (Ministry of Finance) and is responsible for the natural gas infrastructure. Gasunie is the owner of the high-pressure natural gas transmission grid, and facilitates the use of pipelines, liquefied natural gas facilities located near Rotterdam and gas storage. Gasunie mentions an expected increase in green gas in the order of 2.2 bcm (70 PJ) in 2030 (Gasunie, 2016). Gasunie Transport Services (GTS) is a subsidiary company of Gasunie and is the transmission system operator (TSO). They are responsible for management, functionality and development of the Dutch transmission grid (Gasunie, 2018). The TSO, GTS expects a shifting role of gas to a more supporting role to facilitate decentralised energy sources (GTS, 2016). Distribution system operators (DSOs) manage the low-pressure distribution grid, such as Alliander and Enexis. The DSOs are directly or indirectly owned by the national government, provinces, municipalities or other public bodies (Electricity Act, 1998, art 93-2; Gas Act, 2000, art 85-2). Enexis is in favour of green gas, since their revenue depends on the use of their grid, based on capacity and not on volumes (personal communication with M. van Dam, Enexis on 10-03-2015). The risk for the DSO when it comes to loss of revenue, is in disconnection of the residential sector, from the existing distribution grid. This could lead to shorter depreciation periods for infrastructure then estimated, but they expect to distribute green gas instead of natural gas in the future (Enexis, 2016). Besides that, there are energy supply companies that use the grid in order to supply energy to the end-users, in this case the residential sector.

The delineation on a sectoral basis emphasises the large involvement of the Dutch state in the natural gas regime. The contribution to the national income has, however, rapidly decreased from 15.4% in 2013 to 0.8% in 2016, due to decreased production and lower energy prices (CBS, 2017c). The latest projection for natural gas production from the Groningen field stems from 2013 (Ministry of Economic Affairs, 2013). The additional annual reviews (2014–2016) do not provide a long term projection, due to ongoing research on induced earthquakes (Ministry of Economic Affairs, 2014; 2015; 2016). The insecure future production rates comprise a risk for the existing natural gas regime responsible for the supply of heat in the residential sector. High expectations for green gas are present for a longer time in the natural gas regime. The trade, infrastructure and transmission companies in the natural gas regime show awareness of a changing role for natural gas, since an increase in green gas is expected.

Given the expected quantities of green gas, large scale production is required. The expressed expectations in 2011 for green gas production in 2016 by GasTerra are a factor five lower than the actual produced quantities. In addition, in order to end up with 95 PJ green gas in 2030, current quantities purchased by GasTerra should increase fiftyfold. When produced with biomass gasification the required installed capacity is in the order of 5 GW, assuming an efficiency of 70% (Zwart et al., 2006) and 7500 h of production per year. A strategy concerning who is responsible, or how the future production of green gas should be addressed, is not presented by these central companies.

5.4 Discussion

This section is used for two purposes. First, to discuss the methodological choice for the delineation of the regime on a sectoral basis. Second, to deepen the presentation of the opportunities and barriers for the use of green gas from biomass gasification in the Dutch residential sector.

A delineation of the regime on a sectoral basis is sufficient to explain the inertia in the natural gas regime (Markard and Truffer, 2008). A regime shift, which is challenging to address when defining a regime on a sectoral basis (Markard and Truffer, 2008) is not explored here. Hence, biomass gasification technology for green gas can be considered an incremental innovation and its future contribution is therefore not expected to result in a regime shift. This is in line with Geels (2002), who argues that regimes generate incremental innovation and therefore this paper looked at the possible contribution of the natural gas regime to the diffusion of biomass gasification technology. In addition, Kern (2015) states that scientific literature addressing the diffusion of renewable energy technologies shows little evidence of “creative destruction”; renewable energy technologies are often complementary to the existing regime and do not overthrow incumbent regimes. In this research, energy policy was analysed as a landscape pressure on the natural gas regime. The landscape level comprises a variety of insecure and unpredictable pressures on the natural gas regime that may or may not provide incentives to adjust the heat supply system. However, political ideologies, societal values, beliefs, and concerns, which are part of the landscape level are implicitly taken into account by this approach, since the Dutch energy policy is an outcome of agreements with a large number of involved parties (SER, 2013).

In the following, the observed opportunities and barriers are presented from a political, economic, societal and technological perspective, from both the demand and supply side.

The demand side is subject to technological lock-in, due to an absent infrastructure for alternative heat supply. This holds for both private owners and housing corporations with its tenants. The dependency on low-caloric natural gas from the Groningen field is, however, going to change. Given the technological lock-in; green gas, and thus, change on the supply side, is an obvious solution when the dependency on natural gas is to be reduced. From a societal point of view, large scale green gas production with biomass gasification has a preference over other renewable alternatives in the Dutch residential sector, since the use of green gas requires no technological adjustments. Technological adjustments on the demand side are limited by social and economic barriers. In the case of tenants, the insecure effect of increased insulation on their monthly cost, combined with little interest in the energy performance of their residence, hampers change. In addition, housing corporations argue to have limited financial means for investments and find it difficult to convince tenants to accept increased rent prices in order to generate the financial means for investments. Private owners can be considered captive customers. Hence, a switch to another technology requires large investments in insulation and for example, a heat pump. Increasing the amount of insulation reduces the natural gas consumption, which can result in a subconscious lock-in effect where the residential sector does not feel the economic incentive to switch from natural gas to another heating technology. The current aim to have energy performance certificates B and C, for respectively the property of housing corporations and the private sector, in 2020 (Ministry of BZK, 2012) could actually facilitate such a subconscious lock-in, by stimulating insulation measures.

These technological, social and economic factors emphasise the challenge to generate change on the demand side and guide the transition to a sustainable heat supply system. There is a large potential market for green gas from biomass gasification, given the aim to have a decarbonised building stock in 2050 (European Commission, 2018) and the currently lagging technological change and lock-in of the Dutch residential sector. The development of the potential green gas market is, however, affected by the natural gas prices (which are expected to rise), the availability of biomass feedstock, and the implementation of the biomass gasification technology to produce green gas on a large scale.

On the supply side the technological barrier is the upscaling of the biomass gasification technology. This upscaling is hampered, because of the high investment risk and unpredictable biomass prices. In addition, there is no clear policy on the expected role of biomass gasification for green gas. The key players in the natural gas regime have expressed clear expectations for green gas, but hesitate to take a risk by investing in gasification technology on a large scale. Therefore, this technological barrier can be regarded as the result of an economic and political barrier. The natural gas regime does not take responsibility, guidance on a political level is absent and subsequently, the gasification technology developers cannot get past the demonstration phase. A possible solution to overcome this status quo may be by public private partnerships or joint ventures. Fantozzi et al. (2014) argue that such partnerships could reduce risks for private parties and can link technology to the market or the needs on the demand side. They illustrate this by analysing the economic feasibility of two cases in Greece and Italy, where the different risks related to bioenergy projects are allocated to public and private parties.

Such a joint venture strategy could be an option in the Netherlands to link large scale biomass gasification to the potential market for green gas in the Dutch residential sector. This requires, on a political level, not only a facilitating, but also a guiding role on the implementation of bioenergy technologies. A guiding role with a clear vision from the national government is difficult to establish, since the Dutch energy policy is the result of agreements with many parties. However, section 3.4 shows the large in involvement of the Dutch government in the natural gas regime, suggesting that such structures should also be possible in bioenergy projects.

Aside from the implementation of biomass gasification technology, the availability of biomass for energy remains an insecure factor. Shortages in domestic biomass supply of a factor two to nine are expected in 2030 (Commissie Corbey, 2014), therefore import of biomass will be required. International supply chains to realise biomass imports can be feasible from an economic perspective (Uslu et al., 2008). The potential market for green gas from biomass gasification in the residential sector can correspond with multiple gigawatts installed capacity, emphasising the need for the development of such international biomass supply chains. Given the expected domestic shortages and the potentially large demand, such international supply chains need dedicated energy crop production systems.

5.5 Conclusion

This research emphasised the large challenges with which the Netherlands is confronted; the expected depletion of the Groningen field, induced earthquakes in the production area and the large residential dependence on this field. Therefore, the barriers and opportunities for biomass gasification to supply green gas to the Dutch residential sector were explored.

From a supply perspective, the TIS analysis showed that there are four limitations that hamper the diffusion of biomass gasification for green gas, which are systemic barriers mainly related to institutional challenges and financial and knowledge infrastructure. A substantial contribution of biomass gasification on the short term in the Netherlands is therefore not obvious. On the demand side, i.e. the residential sector, the rate of change related to energy performance is behind schedule. In the rental sector this is due to limited financial means, absence of a market model and policy agreements, which are not binding. Resistance of tenants to change, due to lack of interest in energy performance and/or insecurity about the effect on their monthly cost, are therefore difficult to overcome. In the private sector, the absence of mandatory policy and lack of awareness hamper change in energy performance. In addition, for both the housing corporations and the private owners, the absence of infrastructure offers technical risks, and have a negative effect on implementation of renewable heat technology and energy performance. The absence of a market model results in lack of implementation on both the demand and supply side.

In conclusion, there are optimistic expectations for green gas both on a governmental level and by key players in the natural gas regime. The lagging developments in the residential sector and the issues related to depletion and induced earthquakes emphasise the urgency to change. Theoretically, green gas is an ideal solution to address the challenges the Dutch residential sector currently faces, but in practice there is no strategy concerning the implementation of the required technology. In addition, the required technology to produce green gas is not ready for large scale implementation. Key players in the natural gas regime take no substantial responsibility, despite their potential ability to contribute to the systemic barriers related to knowledge and financial infrastructure. This emphasises that the shift towards a sustainable heat supply system in the residential sector requires policy aimed to overcome institutional barriers and a clear implementation plan that is mandatory for all parties on the demand and supply side. Substantial risk capital is absent, but required, if the goal is to produce substantial quantities of green gas. The natural gas regime can foresee in this requirement, but incentives to do so are absent. In addition, the government can stimulate this with technology specific policy, substantial R&D subsidies and funding. When the green gas ambitions are to be reached in the Netherlands in 2030, substantial policy pressures should occur on the short term. Assuming that such pressures occur, then the key players in the natural gas regime can contribute to the diffusion of biomass gasification technology.

6

Conclusion and discussion

"Modern man has turned his back on old philosophies, […] what use are logic, power and wealth with no society".

-Threshold - Wounded Land - Days of Dearth (1993)

Chapter information	
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6.1 General introduction

This thesis started its introductory chapter with the current challenges humankind faces, related to resource dependency and climate change due to global pollution. These challenges and the ambitions put forward by the Paris Agreement, to remain well below a global mean temperature increase of 2°C compared to pre-industrial times (United Nations, 2015), require an energy transition. It appears that system change is required in order to have a successful energy transition. In this thesis, system change is regarded as the change required for an energy transition to a sustainable energy system, where current carbon dependency is overcome. From literature we know that such system change is comprised of a multitude of factors, such as, technology, politics, economics and its interactions (Geels, 2011). Currently, technological innovation is seen as important in European policy (European Commission, 2015a) as a force to solve the challenges related to the energy transition. Some technological innovations are addressed in this PhD thesis with the analysis of the contribution and limitations of three technological innovations. The innovations are, the introduction of electric vehicles, co-combustion of biomass in a coal-fired power plant and biomass gasification technology for the large scale production of green gas. This thesis focused mainly on technological innovation (i.e. electric vehicles, biomass co-combustion and biomass gasification) as a force for the energy transition, in chapters 2-4. However, the importance of the other factors, besides technology, is recognised. Therefore, chapter 5 was applied to explore the interaction between economics, politics and technology. This was done by looking at the potentials and limitations of biomass gasification technology for heat supply in the Dutch residential sector.

This final chapter is organised as follows. The most important conclusions from the explored innovations are presented in section 6.2. This section is also used to provide an answer to the overarching research question; to what extent do some technological innovations, contribute to the energy transition? Subsequently, section 6.3 is applied to reflect on the results from this thesis. It first reflects on the different cases discussed in chapters 2-5, and identifies some causes to explain the results. The second part is the general reflection, which looks at the role of innovation and politics in a system where demand continues to increase**.** This thesis studied three sectors, namely the residential, energy and private transportation sector. The final section 6.4 is used to explore some options for the required energy transition in these sectors. Aside from looking at the role of technology, this section discusses some implications of system change by addressing the possible role of factors, such as economy and politics.

6.2 General conclusions

This section gives an overview of the most important conclusions of the three explored innovations in order to answer the main research question of this thesis.

6.2.1 Lithium and battery electric vehicles

Chapter 2 explored the potential contribution of electric vehicles in the European Union (EU) to the energy transition. The availability of lithium for vehicle batteries, and thus an increased flowrate of lithium into society, is the bottle-neck for implementation of such an end-of-pipe solution. Hence, electric vehicles may have no tailpipe emissions, but the overall emissions from transportation are not guaranteed to decrease when the energy supply system is not adjusted. The main factors affecting the future lithium availability for electric vehicles were determined. The chosen values for these factors were quite optimistic, which was argued to result in the determination of the lower boundaries for lithium demand per vehicle and upper boundaries for vehicle penetration rates. The projected lithium supply curve assumed a doubling of supply in a period of 10 years (i.e. growth rates of 8% per year).

The results from chapter 2 show that due to the estimated supply limitations on lithium for batteries, a full electric scenario results in 95 million battery electric vehicles in 2050; corresponding to 20% of the total fleet. The estimated absolute increase in vehicles in the EU between 2000 and 2030 is estimated to be 146 million. This means that even when high penetration rates of battery electric vehicles are realised, the absolute amount of conventional vehicles still increases, resulting in a transport sector performing worse from a climate perspective. Full adoption of plugin hybrid electric vehicles instead of battery electric vehicles is possible in 2050, due to smaller lithium demand. Such a scenario can potentially result in a reduction in gasoline use of about 40%, which is a much larger efficiency increase than the 20% when battery electric vehicles are introduced. Given the estimated supply limitations on lithium, the results emphasise that small adjustments to the whole private transport sector (i.e. full plugin hybrid electric vehicle adoption) have a more positive effect than relatively large adjustments to 20% of the transport sector. This holds for both a CO_2 emissions and energy efficiency perspective. Electrification of the vehicle fleet can contribute to the mitigation of climate change when plugin hybrid electric vehicles are introduced on a large scale. However, such small adjustments do not result in the required energy transition in transportation, since it would legitimise continued use of fossil fuels. In addition, the challenges related to greenhouse gas (GHG) emissions in transportation are also not solved with the large scale introduction of battery electric vehicles, due to the limitations on supply of lithium.

Thus, the actual introduction of electric vehicles should be regarded as an efficiency improvement of the existing private transportation system, on the short term, and not so much as an innovation that contributes to system change. Due to continued expansion of the private transportation sector, electric vehicles, only have a short term, and very limited, effect on the energy transition. Increasing the efficiency of the private transportation systems with electric vehicles, results in increased GHG emissions on the long term, as long as the mobility system continues to expand.

6.2.2 Co-combustion of biomass and coal

Chapter 3 explored the climate contribution of co-combustion of biomass in a coal-fired power plant. In this case the energy efficiency of the supply system decreases. Co-combustion of 10% biomass on an energy basis only results in 4% to 7.5% reduction in GHG emissions and a 4% to 6.5% increase in renewable energy. Thus, roughly half of the potential decrease in emissions and half of the energy content of biomass is annihilated by decreased supply chain and conversion efficiency. In the cases where 60% biomass is co-combusted, GHG emissions can be reduced with almost 50%. This is a large potential, but an emission reduction of such magnitude can also be achieved by simply replacing coal with natural gas for electricity production. In that case one would not require a doubling of mass transport and the development of a large logistic system for biomass production and supply.

In addition, the temporal dimension was not taken into account in the co-combustion scenarios. When the absolute electricity demand increases over time, the net effect of co-combustion on the reduction of GHG emissions can very well be negligible or even negative, especially in the cases where small quantities of biomass are co-combusted.

6.2.3 Biomass production for green gas supply

Given the expected limitations on future supply of biomass in 2050, which are a factor two to four lower (Laugs and Moll, 2017) than current global energy use, the need to use biomass as efficient as possible is clear. Therefore, another option for the use of biomass for energy was explored in chapter 4: green gas production through biomass gasification. This technological innovation is accompanied with high expectations, since it can theoretically produce a green gas with an efficiency of 70%, which can be converted to electricity with a combined cycle gas turbine with efficiencies around 60%. However, such high efficiencies do not take away the limitations on supply. Indigenous supply of biomass from extensive systems within the EU is limited (Asikainen, 2008). When looking at extensive production systems, like forests, where the annual increment can be sustainably harvested, its possible contribution to the supply of energy is marginal. Such extensive production systems cannot foresee in the required amounts of renewable energy. Hence, 16% of the technically available biomass from extensive systems is required to foresee in 1% of the European natural gas consumption. Application of gasification technology with biomass as feedstock for green gas from intensive production systems would require 140% of the arable land currently in use in the EU, when aiming to replace the total natural gas demand and assuming no increase in demand. When taking into account that natural gas contributes for 25% to the total demand in the EU, replacing substantial quantities of fossil carbon with renewable carbon in the EU must result in biomass imports from all over the world and with that a shift in geographical resource dependency. The explored supply chains for large scale green gas production show that the energy efficiency and energy ratio performance are always worse than the reference scenario of natural gas. GHG emission reductions can, however, be substantial, up to almost 70% when transport logistics are optimised and torrefaction of the biomass is applied. Green gas, via biomass gasification, can potentially contribute to the energy transition on the long term. Its contribution is limited by the available biomass quantities, since the potential domestic production in the EU is small.

Besides availability, there is the increase in transport movements within the EU, which is substantial when using biomass on a large scale. Replacing 1% of the natural gas consumption with green gas in the EU already showed limitations, whilst this 1% corresponds with about one-tenth of the annual increase required to fulfil the targets formulated for renewable energy in 2020. Besides this, the energy requirements for transport of biomass can be 1.7 to 6.4 times higher than natural gas supply via pipelines. Additionally, this thesis showed that there is no energetic advantage in pretreatment of biomass when looking at transport. Hence, the savings in transport energy, due to increased energy density of the biomass, are neutralised by the energy cost for pretreatment. Increasing the energy density of biomass before transport, may affect the conversion efficiency of the biomass, but increases the total energy consumed in the supply chain.

6.2.4 Green gas implementation in the Dutch residential sector

Besides the aforementioned availability of biomass, the effect on transport logistics and shifting geographical dependency, there is the question of actual large scale diffusion of biomass gasification technology for green gas production. Therefore, this thesis looked at a case where the possible contribution of biomass gasification technology for the supply of heat in the Dutch residential sector was explored. The ambitions for green gas use in the Netherlands are high and there is large potential for green gas supply to the Dutch residential sector given their large dependency on the use of natural gas for heating purposes. Such quantities require large scale production. Biomass gasification technology can theoretically address a scale in the order of 5 gigawatt, which is required to supply about a quarter of the current natural gas consumption in the residential sector in the form of green gas. However, the results of this thesis show that a number of factors form barriers for the diffusion of this technology. Four limitations were observed on the supply side. First, the inability to increase the scale on which experimentation with the technology occurs, due to financial constraints. Second, on an institutional level there is absence of technology specific policy. Third is the absence of a substantial market required to foresee in the goals that are set. Fourth is the limitations related to insecure future biomass prices and availability. Financing the commissioning of commercial scale plants is difficult, since the investments are large and the risk is high. Continued technological development and with that upscaling from demonstration to a (pre-)commercial scale is therefore hampered. In addition, this upscaling is also a lengthy process, which given the current state of development, is going to cost a decade at best. Ending up with 5 gigawatts installed capacity in 2030, which is required considering the aimed quantities of green gas, is unfeasible. The substantial challenge with which the Netherlands is confronted in order to develop a sustainable heat supply system is not solved with green gas from biomass gasification.

6.2.5 Contribution to the energy transition: biomass and batteries

The extent to which the explored technological innovations contribute to the energy transition and to the mitigation of climate change is small. On the short term there may be a contribution from electric vehicles, but on the long term, potential increases in energy efficiency of the private transportation system are annihilated by an increasing vehicle fleet. The effect is therefore limited to the short term. For co-combustion the contribution to the energy transition is similar. The effect is confined to the short term, in which it legitimises the continued use of coal. In addition, there is also a material demand for carbon which puts a strain on the potential availability of biomass for energy. Contradictory to the expectations of EU politicians, who see a bright future for electric vehicles and bioenergy, the contribution of these innovations to the energy transition is marginal, especially on the long term. This may have potentially dire consequences, since the expected time remaining to implement the required system change and overcome carbon dependency, to prevent the effects of climate change from becoming acute instead of chronic, is about four decades (chapter 1). An alternative future innovation such as biomass gasification could theoretically contribute to the energy transition, but the time required for diffusion of the technology on a substantial scale is in the order of multiple decades (Karltorp, 2016). In addition, biomass gasification is subject to the same limitations on supply of biomass, as co-combustion.

In conclusion, both electric vehicles with lithium based batteries and biomass for energy are still subject to high expectations during the energy transition, which are, as emphasised by this thesis, not feasible. In two explored cases, (i.e. electric vehicles and biomass co-combustion) the potential contributions to the energy transition in the required time-frame are small. In the case of biomass gasification, it is clear that there may be, at best, a marginal role for this technology within the timeframe where the energy transition should take place.

6.3 Reflection on the results

6.3.1 Reflection on the results from the cases

The introduction of electric vehicles improves the existing private transportation system when looking at energy use and local air pollution. Hence, the energy efficiency is increased, since the energy requirements per unit of distance for a battery electric vehicle are smaller than a conventional vehicle; that is, the conversion from mechanical to kinetic energy is done more efficient in the case of a battery electric vehicle compared to a conventional vehicle. In addition, there are no tailpipe emissions, and when renewable electricity is used, the GHG emissions per unit of distance decrease substantially. Thus, a technological innovation, such as electric vehicles, can improve the private transportation system. However, due to continued expansion of the private transportation system there is no change of the existing system and a negative effect when it comes to a reduction in energy consumption and GHG emissions. This is also visible in historic developments in the EU, where the energy efficiency of transport increased by 15% between 1990 and 2008. In the same timeframe per capita energy consumption in the transport sector increased by 26% (EEA, 2011). Besides this, 2015 sales of electric vehicles, both battery and plugin hybrid electric vehicles, were about 1.2% of the total vehicle sales (EEA, 2016). This emphasises again, that electric vehicles will not contribute substantially to the energy transition, since the required sales numbers are 6.5% in the analysed scenario in chapter 2. There are some exceptions in Europe, such as the Netherlands, where new sales of electric vehicles were almost 10% in 2015. However, in the two consecutive years there was a steep decline to 2.6% (Netherlands Enterprise Agency, 2018). The issue of transportation becomes even more challenging when considering other means of transport like air traffic, which is expected to increase with on average 4.5% per year between 2016 and 2035 (MacDonald, 2017). This means that air traffic will more than double in this period.

Contrary to the case of electric vehicles, where the energy efficiency of the private transportation system as a whole was increased, co-combustion shows a decrease in energy efficiency. When regarding biomass as a renewable energy carrier and its availability as abundant, the decrease in energy efficiency of the system is not an issue, especially since all co-combustion scenarios resulted in a reduction in GHG emissions and the production of renewable energy. This also holds in the case of large scale green gas production, where the energy efficiency is much lower than a reference scenario with natural gas, but GHG emissions do decrease and renewable energy is produced. These arguments to use carbon from biomass as a substitute for fossil carbon to supply energy, legitimise the continued use of coal and natural gas. Therefore, a successful energy transition is hampered by the large scale application of biomass for energy. Despite this, the application of biomass for energy is the norm in the EU, since two-thirds of the current renewable energy production has an organic origin (Eurostat, 2018).

As resource use is interconnected (Verhoef et al., 2004), the implementation of technological innovation in expanding systems is subject to the risk that alleviating dependency of one resource leads to scarcity of another resource. The explored innovations shift dependency from a fossil resource to a potentially scarce resource when such innovations become successful. Martin et al. (2017), showed that production of virgin lithium has roughly doubled between 2000 and 2015. In the same period, the price for Li_2CO_3 increased with a factor 3.5. When looking at current (i.e. 2018) prices, this increase is more than a factor 7 (Ober, 2018). Therefore, the projected discrepancy in supply and demand, and thus scarcity, is already present. Furthermore, large scale introduction of electric vehicles in the EU is limited by the fact that the EU has very limited domestic lithium carbonate resources for batteries; thus, imports from politically sensitive areas are required.

When aiming to apply biomass for energy on a large scale, the EU may become dependent on worldwide imports, which are subject to possible scarcity. This import dependency is likely, given that the available area is a limiting factor (section 6.2.3) and the role for biomass as a renewable energy source is expected to remain substantial in the EU (European Commission, 2016a). In addition, there are various applications for biomass besides energy, such as food, feed, pharmaceuticals and chemicals (European Commission, 2012). Application of biomass for those purposes may become at risk when biomass is used for energy on a large scale (chapter 4). On a small scale, local use of biomass may, however, provide opportunities as a back-up in order to balance other intermittent renewables and guarantee continued supply (Pierie et al., 2017).

The high expectations from the EU, when it comes to the contribution of the explored innovations, are based on the technological potential. These technological innovations are not enough, since the realised increase in energy efficiency cannot keep up with growing demand, and they shift the resource use to other potentially scarce resources, as addressed in this thesis. Therefore, it appears that more is required than technological innovation alone to realise an energy transition. This is in line with existing visions in literature (Alcott, 2005; Geels, 2011; Markard et al., 2012; Walrave and Raven, 2016). Actual diffusion and success of a technological innovation is subject to more factors than technology alone. The social or behavioural aspects in human mobility should also be addressed in order to have a successful energy transition in the transportation sector. The emphasis on reduction of CO_2 emissions in EU policy (European Commission, 2009), in the case of co-combustion, leads to short term effects and no system change that positively affects the energy transition. In addition, chapter 5 showed that it is clear that the gasification technology is subject to a number of factors that hamper its diffusion and potential effect on the energy transition.

In summary, two causes are identified for the small contribution of the explored innovations. First, the innovations contribute to improvement of existing systems, but do not change them. Second, shifting resource demand results in continuous scarcity effects in a system where demand continues to increase.

6.3.2 General reflection

The explored technological innovations do not result in an energy transition, even when policy is present to stimulate these innovations. The question remains whether the combined effects of other technological innovations and the organisation of the alignment of other factors besides technology, such as, politics and economics are enough to realise an energy transition. Therefore, this section first explores insights from literature, about the role of technological innovation in the energy transition. Second, it elaborates on Jevons paradox, path dependence and lock-in to find how the results from this thesis relate to wider insights in literature. Without going into detail about the other factors affecting the energy transition this section finalises with some insights about the effect of current policy resulting from European politics.

The explored technological innovations can be regarded as incremental innovations, which improve that what already exists. Such improved performance actually slows down change of the system. This slow rate of change is also recognised by Kern (2015) and Markard et al. (2012) whom observe that incumbent systems are only subject to incremental adjustments instead of radical ones. Here, radical innovation should be regarded as a new solution that is not based on the existing previous solutions (Beck et al., 2016). In addition to the observed slow change, Kern (2015) argues that structural rigidities within the energy sector hamper a transition. These structural rigidities can be explained by entrenched technology and the accompanied powerful agency of the incumbent energy system (Kern, 2015). Walrave and Raven (2016) and Markard et al., (2012) argue that incremental innovation does not automatically lead to the required system change to foresee in the required adjustments to deal with the challenges humankind currently faces. This shows that the results from chapter 2 – 4 in this thesis are in line with existing visions in literature.

Jevons paradox, or more popular, the rebound effect, is the theory that argues that efficiency increases are annihilated by additional consumption (Polimeni et al., 2015). When demand continues to increase, through a growing population and increasing affluence, technological innovation cannot keep up. Such technological change is also thought to be the actual driver of consumption together with increasing returns to scale (Alcott, 2005). The private transportation system is a perfect example of this paradox. First, efficiency increases on a fuel level were counterbalanced by increased consumption (EEA, 2011), and in addition, this thesis shows that projected future efficiency increases on an engine level are counterbalanced too, for the same reason. Biomass use for energy introduces some change on the supply side, but given Jevons paradox, this is not obvious to have a positive long term effect. Furthermore, in a system where demand continuously grows, technological innovation shifts the consequences of resource use to other environmental domains, which in a finite world always leads to scarcity effects. Thus, as long as technology and economics are applied to stimulate growth and affluence, environmental problems will persist.

Even when technology is pushed with policy it is clear that these technological innovations do not result in an energy transition. It appears that instead of incremental adjustment of the existing system, more radical change is required. Such radical system change is, however, not easily implemented. This inability to induce system change with technological innovation can be explained by the concept of path dependence with lock-in as an outcome. The existing carbon based energy system can be regarded as the outcome of the accumulation of historic decisions. These historic decisions subsequently affect future decisions, independent of the current relevance of these historic circumstances. The accumulation of historic decisions, or path dependence, related to the development of the energy system, is driven by increasing returns to scale and has led to a state of carbon lock-in. The historic decisions have led to the establishment of the carbon based fossil energy system in a techno-institutional context. Unruh (2000), explains that over time, not only technology, but also the institutions were adjusted in order to increase this energy system. Currently, the same institutions slow down the diffusion of renewable energy technology. This so-called carbon lock-in leads to policy failures that hamper the diffusion of renewable energy technology (Unruh, 2000).

On a political level, the illusion that the optimisation of three policy objectives of the EU, namely security of supply, economic competitiveness and the environmental objective, will result in a successful energy transition is still present. On the short term, incremental innovation is the optimal solution for security of supply and economic competitiveness. On the long term, however, these objectives are not guaranteed when shifting to potentially scarce resources, nor does a successful energy transition happen. Thus, within the existing economic system driven by growth, the three objectives of EU energy policy do not lead to the required energy transition and the transformation of the energy system. Proposed policies, such as the bioeconomy strategy (European Commission, 2012) where linear cascading of biomass based on economic value is introduced (figure 1-1), results in more efficient use of resources. The same holds for the circular economy strategy where, due to increased recycling and reuse, the burden on virgin materials is decreased (European Commission, 2015b). As elaborated, increasing efficiency does not appear to solve the problems that society is confronted with, and therefore, as long as demand increases, such policies only postpone the consequences of resource consumption on to future generations.

The advantage of incremental over radical innovation is that it can contribute to all three objectives of European policy. For example, prices for electricity from coal were the lowest in 12 years in 2016 (European Commission, 2016b). This has a positive effect on the affordability and the security of supply; the combination with an incremental innovation such as biomass co-combustion in a coal power plant decreases the environmental burden, since emissions of fossil carbon per unit output are decreased. Besides that, such adjustments are relatively easy to realise within the short term horizon of national politics. Additionally, such a power plant has an economic and technical life time in the order of 35 and 50 years, legitimising continued use of fossil fuel. This suggests that incremental innovation is the “optimal” trade-off between the three objectives of European energy policy. The success of the energy transition is therefore endangered by a trade-off between these three policy targets. Thus, incremental innovation is driven by EU policy, which actually reinforces system lock-in instead of overcoming it.

6.4 Exploration of options

The first chapter of this thesis explained the need for an energy transition. Hence, the large scale combustion of fossil fuels for energy purposes has led to depletion of fossil resources and climate change. Subsequently, this thesis looked at technological innovations, which are expected to contribute to this transition. Incremental innovation in itself is argued not to overcome the existing challenges and the focus should therefore be, on replacing existing systems (Geels, 2011; Markard et al., 2012; Kern, 2015; Kivimaa and Kern, 2016; Walrave and Raven, 2016). The existing challenges are clearly not overcome by the innovations addressed in this thesis. In order to have a successful energy transition, technology push policy can be an option, when the need for the potential purpose of the technology is recognised and its introduction is stimulated. For example, gasification technology can be stimulated in such a way that biomass is used on the short term for energy, where it can have a positive effect. On the long term gasification technology may have potential in a circular economy where it uses carbon containing waste as feedstock instead of biomass. This does require a clear vision of a future sustainable energy system in order to determine which technology should be stimulated with which purpose or application. Such a vision should therefore also integrate other factors influencing the energy transition in order to realise the implementation of this vision and with that the energy transition. For example, chapter 5 showed that there is a vision in the Netherlands, addressing future heat supply, where green gas also plays a role. The applied frameworks (i.e. the multi-level perspective and the technological innovation systems) in chapter 5 show that the embedding of biomass gasification technology and the organisational aspect related to heat supply with green gas, are barriers hampering its implementation. Hence, a number of institutional and infrastructural aspects were observed on the supply side, that slow down the diffusion of the technology. In addition, on the demand side there are economic constraints and institutional barriers. Therefore, not only should a clear vision be developed addressing the design of a sustainable energy system from a technological perspective, but also how the energy transition towards this sustainable system should be realised from an institutional and infrastructural perspective. For the three explored sectors in this thesis, private transportation, large scale energy supply and the residential sector, this has some implications on how to embed new technology and organise its implementation. To finalise this thesis, some options, related to technological, economic and social factors are provided to address some implications for the sectors studied in this research.

In transportation, a decrease in resource consumption can be achieved by a shift to the use of public instead of private transportation, requiring many adjustments. Driving such change requires compelling policy, enforcing the development of such a new system and the required behavioural change. The actual performance of such a system for the environment and the consumer, should be the main objective, instead of economic growth. This requires more adjustments than shifting the means of transportation, but actual reconsideration of the necessity of transportation. Technological change can contribute, for example by introducing more efficient ways to communicate in a work environment without the need for people to be in the same physical location. This does however, require substantial adjustments on the consumption side. Options to overcome potential barriers for the consumer may be found in improved transport networks of public and other types of transportation, such as car sharing and the combination of buses and bicycles (Cruz, I. S., & Katz-Gerro, 2016). In addition, no financial compensation for commuting with private transport can be an option, which is an example of an economic incentive to stimulate desirable behaviour.

When it comes to the supply of power, an option can be to develop decentralised self-sustaining communities and the use of renewable sources, which are not subject to economic scarcity, like solar and wind. Secondary energy carriers such as hydrogen can be applied for storage or as a transportation fuel (Koirala et al., 2016). However, such systems do depend on light and heavy rare earths and platinum group metals which may also be or become subject to scarcity issues and import dependency (European Commission, 2017b; De Boer and Lammertsma, 2013). In addition, the role for consumers is large in such small decentralised communities, which requires substantial social adjustments. The encouragement of such adjusted behaviour on the consumer side needs governmental support, not only with financial means, but also by engaging local communities in its decision-making (Bomberg and McEwen, 2012).

In the Dutch residential sector, substantial adjustments in insulation levels should be realised in order to decrease demand for heat by renovation of existing dwellings (Olonscheck et al., 2015). Additionally, in line with the aforementioned scale reduction, options for heat supply can be organised through local heat grids, supplied with heat from, seasonal storage of solar heat, geothermal energy and waste heat from industry. Biomass gasification can potentially contribute with green gas as a back-up for heat supply, using local biomass on a smaller scale. In this case it should be applied in areas with limited renewable energy available, such as old city centres, or in rural areas, when there is no business case for large heat grids. This requires a clear long term vision and even more important a clear implementation plan from politics, on which technology should be pushed and with which purpose.

This thesis started with a quote believed to originate from the Greek philosopher Socrates, arguing that one should focus on building the new instead of fighting the old in order to induce change. However, instead of fighting the old, or building the new, the optimal trade-off between the three objectives of EU energy policy results in incremental innovation of technology, which in practice, results in improvement and continued legitimisation of that what already exists. The most important global agreement to address climate change is the Paris Agreement (United Nations, 2015). It literally states, "[a]ccelerating, encouraging and enabling innovation is critical for an effective, long term global response to climate change and promoting economic growth and sustainable development". Unfortunately, the part about promoting economic growth and sustainable development is not an oxymoron, but a contradiction in terms given the finite amount of resources available. Given the timeframe that remains to introduce the required change, in order to have a successful energy transition, substantial change should not be expected from technology alone. Policy should therefore aim to simultaneously realise change on a societal, institutional, political and economic level. A clear vision on what such a system should look like should be developed through scenarios. Additionally, pathways should be developed on how to arrive in such a system and the required measures for implementation have to be enforced to realise the energy transition.

7

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“Employ your time in improving yourself by other men's writings, so that you shall gain easily what others have laboured hard for”.

-Socrates-


schatte
HUMANS before HUMANITY
FOLEY
Binas
DEAD AID
DAMBISA MOYO
ALLEN LANE
Disney
Donald Duck HISTORY
1
GEORGE ORWELL
NINETEEN EIGHTY-FOUR
ALAN WEISMAN
THE WORLD WITHOUT US
PICADOR
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Appendices

Forerunner of the electric car developed by professor Sibrandus Stratingh from the University of Groningen (ca 1835).

Appendix A Calculation of the modal energy intensity and load limitations

The modal energy intensities are assumed to be linear to the mass load. Based on the data from Giuntoli et al. (2015) the energy consumption for transport by truck and Supramax bulk carrier are calculated to be, respectively;

$$f(x)_{Truck} = -2.1 \cdot 10^{-2}x + 1.1 \ (0 \leq x \leq 26) \quad \text{(A-1)}$$

$$f(x)_{Supramax} = -2.8 \cdot 10^{-6}x + 0.2 \ (0 \leq x \leq 54x10^{3}) \quad \text{(A-2)}$$

Where x represents the (limited) mass load (in t) and $f(x)$ the modal energy intensity (in MJ/tkm). Table A-1 gives the maximum mass loads for low, average and high bulk densities of coal, wood chips, torrefied wood chips, pellets and TOP. When the mass load is smaller than the net payload (26t for trucks and 54000t for the bulk carrier), the load is volume limited. The difference of 1t load between coal and pellets and TOP is due to specific truck requirements for pellet transport. This paper applies a value of 1t for these requirements in line with Giuntoli et al. (2015). The transport of wood chips with a low bulk density is volume limited, just as the low and average bulk densities of torrefied wood chips. For overseas transport by Supramax, there is a volume limitation for chipped wood, torrefied wood chips and pellets for low to high bulk densities. The average bulk densities in table 3-3 were applied to calculate the maximum mass loads for a 40t truck and the Supramax bulk carrier. These mass loads (table A-1) represent x in equations A-1 and A-2. With equations A-1 and A-2, the modal energy intensity was determined for both transport modes. The modal energy intensities are presented in figure A-1; error bars are included when relevant, that is, when volume limitations are present (see also table A-1). The modal energy density for trucks with woodchips is applied for this research, since further pretreatment is executed at the harbour, before overseas transport.

Table A-1: The maximum load (t) of truck and Supramax bulk carrier for coal and biomass for low, average and high bulk densities.

		Maximum load (t)				
		Coal	Chipping	Torrefaction	Pelleting	TOP
Truck	Low	26	18	21	25	25
	Average	26	26	24	25	25
	High	26	26	26	25	25
Supramax	Low	54000	14400	16560	36000	54000
	Average	54000	23400	19080	41400	54000
	High	54000	32400	21600	46800	54000

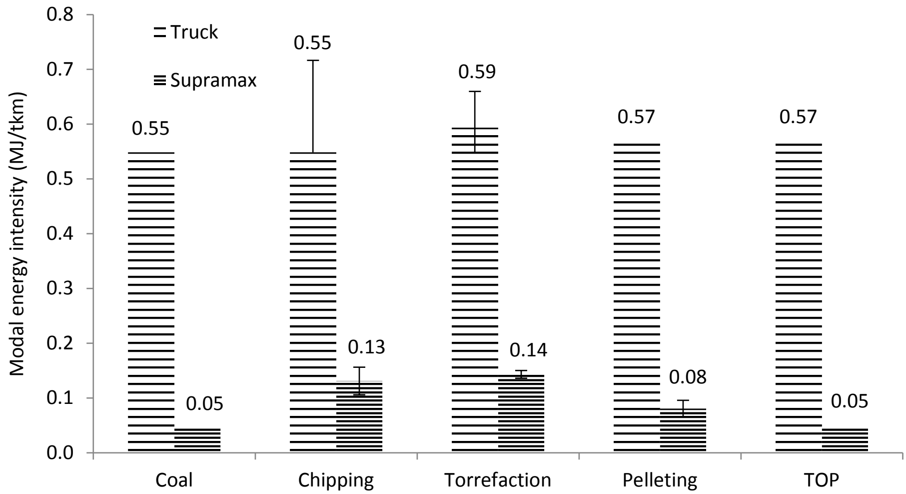

Figure A-1: Calculated modal energy intensity for truck and bulk carrier.
Transporting of coal, wood chips, torrefied wood chips, pellets or TOP. The labels in this figure refer to the specific modal energy intensity for truck or Supramax and not to the error bars.

Appendix B Overview of the energy consumption and GHG emissions in the supply chain scenarios

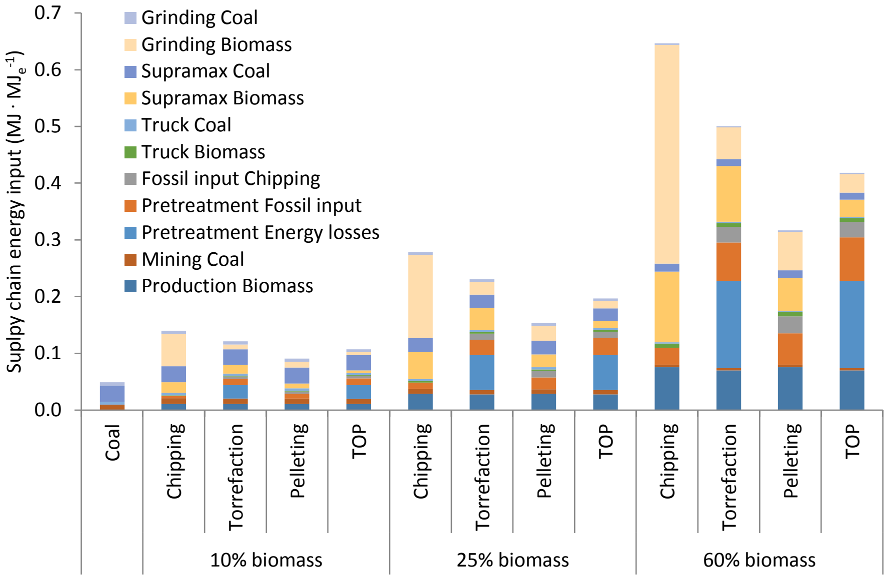

Figure B-1: Detailed overview of the supply chain energy consumption without conversion.

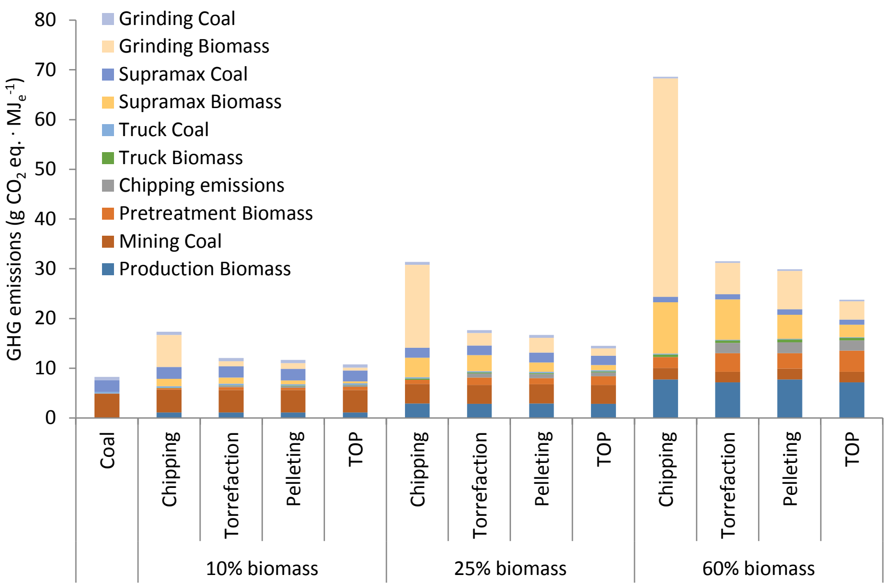

Figure B-2: Detailed overview of the supply chain GHG emissions without conversion.

APPENDICES

Summary

Biomass or batteries: the role of three technological innovations in the energy transition.


P
Electric
Vehicles
Only
EVBOX

Introduction

Mankind is on the verge of an energy transition, during which society has to shift from a dependency on fossil fuels towards the use of renewable energy. Currently, about 10% of the final energy consumption originates from modern renewables. The aim of the Paris Agreement is to mitigate the consequences of climate change by keeping the increase in global mean temperature below 2°C. Given the current emissions of greenhouse gases (GHG) and the remaining carbon budget, from now on, a linear decrease should be realised towards zero emissions around 2060, in order to have a successful energy transition. In addition to the mitigation of climate change, by reducing GHG emissions, there is a second argument to organise an energy transition, namely resource depletion. Recent estimates for the ratio of reserves over production, for oil, natural gas and coal are, respectively 50, 52 and 153 years. Despite the clear arguments in favour of an energy transition, such as mitigating climate change and reducing the dependency on finite resources, a transition is not a straightforward procedure.

An energy transition requires system change. Here, system change is regarded as the change to a sustainable energy system, where current carbon dependency is overcome. This is a challenge, since industrialised countries have become addicted to the use of fossil fuels to foresee in continued economic growth and increasing consumption. The fossil based energy system is a complex system where the combination of and interaction between technologic, institutional and societal factors hampers change; this is also known as carbon lock-in. The challenge of system change can be understood with the concept of path dependence that ultimately led to carbon lock-in. The existing carbon based energy system can be regarded as the outcome of the accumulation of historic decisions. These decisions subsequently affect future decisions, independent of the current relevance of these historic circumstances. The accumulation of these decisions, related to the development of the energy system, is driven by increasing returns to scale and has therefore led to a state of carbon lock-in.

A number of factors is known to affect system change, of which policy is regarded as an important one. The European Union (EU) aims to play a role in guiding the energy transition, since the EU put a variety of energy policy in place and ratified the Paris Agreement. Innovation plays a key role in the policy put forward by the EU and, in addition, the expectations for the role of technology in the energy transition are high.

The question remains whether technological innovation is enough to overcome the challenges of climate change and resource depletion within the remaining timeframe. Therefore, the main aim of this thesis is to explore the potential contribution of three technological innovations to the energy transition. Cases are studied addressing two crucial materials, namely lithium and biomass, and three sectors, namely private transportation, energy production and the residential sector.

Lithium availability in the European Union for electric vehicles

The adverse impacts of climate change are widely recognized as well as the importance of the mitigation of carbon dioxide (CO_2). Therefore, battery driven vehicles are expected to have a bright future, since GHG emissions can be reduced, since the efficiency of these vehicles is higher than conventional vehicles and there are no tail-pipe emissions. Lithium-ion (Li-ion) batteries appear to be the most promising, due to their high energy density. The current challenge is the needed increase in flow rate of lithium carbonate (Li_2CO_3) into society to foresee in the forecasted demand.

This research determines ten factors which influence the availability of Li-ion batteries for the EU in the coming decades. They are used in a system dynamics analysis, where the stocks, flows and feedback loops of the system were analysed. The results of this research show that undersupply of Li_2CO_3 can be expected to be between 0.5 to 2.8 Mt in the EU, until 2045. Substitution of Li_2CO_3 in other end-use markets and recycling can relieve the strain on Li_2CO_3 supply to some extent. The increase in flowrate of Li_2CO_3 is limited and therefore, 20% of the vehicle fleet in the EU can be battery electric vehicles (BEVs) in 2050. The lack of resources in the EU and the geographical distribution of Li_2CO_3 in politically sensitive areas suggest that the shares of Li_2CO_3 available for the EU will be even less than assumed in this research.

An alternative way to apply the available Li_2CO_3 is by producing plug-in hybrid vehicles (PHEVs). They require less Li_2CO_3 and therefore a 100% PHEV scenario is feasible in 2050. This would result in a more substantial decrease in tailpipe emissions of the total vehicle fleet, compared to the introduction of 20% BEVs. This has a positive effect on climate change, but it does not contribute to a decrease in carbon dependency and it is subject to the risk of postponing the consequences of climate change further into the future instead of mitigating climate change.
The increase in flow rate shows to be the bottle-neck for a transition to BEVs in the EU, at least when Li-ion batteries are used. The large scale application of BEVs with Li-ion batteries in order to substantially mitigate CO_2 emissions in transport and reduce dependency on liquid fossil based fuels is therefore not guaranteed.

Biomass co-combustion in a coal-fired power plant

In the last century, coal combustion has been widely applied for electricity generation. Coal is known to be the most polluting fossil fuel. Despite this, the lock-in effects of coal firing power plants have increased, due to cheap emission certificates, low coal prices and deregulation of the European power sector. A variety of technological innovations is available to decrease the environmental impact from coal combustion, such as carbon capture and storage, increasing boiler efficiency and co-combustion of coal with biomass. This thesis explored the contribution to the mitigation of climate change of biomass co-combustion. A variety of supply chain scenarios were analysed, for different co-combustion scenarios in coal-fired power plants. They were analysed on energy efficiency, energy consumption, renewable energy production and GHG emissions and subsequently compared with the performance of a 100% coal supply chain scenario, in the Netherlands. Calculations were executed for biomass shares of 10%, 25% and 60% in the form of wood chips, pellets, torrefied wood and a combination of torrefied and subsequently pelletized (TOP) wood.

The 60% biomass co-combustion supply chain scenarios show possibilities to reduce emissions up to 48%, assuming that biomass is carbon neutral. The low co-combustion levels are effective to reduce GHG emissions, but the margins are small. Currently, co-combustion of pellets is the norm, but co-combustion of TOP shows the best results, but is also the most speculative. In addition, the scenarios showed that the indicators from the Renewable Energy Directive, which aims to promote the use of energy from renewable sources, cannot be aligned. These indicators are, GHG emission reduction, renewable energy production, increased energy efficiency and decreased energy consumption. Hence, GHG emissions are decreased in all scenarios, but the total energy consumption increases.

In conclusion the results show that when biomass is regarded as scarce, co-combustion of small shares or no co-combustion is the best option from an energy perspective. When biomass is regarded as abundant, co-combustion of large shares is the best option from a GHG reduction perspective.

Chain analysis of biomass gasification for synthetic natural gas

Woody lignocellulosic biomass can be co-combusted with coal, but an alternative application may be thermo-chemical conversion into a green gas, or synthetic natural gas, with biomass gasification technology. This synthetic natural gas has properties similar to natural gas, making it suitable for injection into the existing supply grid. A quarter of the total primary energy demand in the EU is met by natural gas, providing opportunities for the large scale application of synthetic natural gas. Synthetic natural gas produced through biomass gasification can contribute to a more sustainable energy supply system, since GHG emissions may be reduced. The performance of the possible large scale application of biomass gasification for synthetic natural gas production should be determined by a supply chain analysis where the upstream, midstream and downstream part are included. Therefore, in order to find the energy performance and GHG emission reduction potential of biomass gasification, a chain analysis of synthetic natural gas, was undertaken. A variety of supply chain scenarios was explored where dry wood chips, wood pellets and torrefied wood were compared. A model was designed to analyse the performance of the biomass to synthetic natural gas chain and to estimate the impact of 1% synthetic natural gas in the energy system.

This 1% represents 0.25% of the primary energy demand of the EU and can result in reduction of GHG emissions of almost 70% at the cost of 1.3 Mha of arable land. Replacing the use of natural gas in the EU with synthetic natural gas would require 140% of the arable land currently in use, which emphasises the risk of upcoming import dependency on biomass if such a system would be applied on a large scale. In order to optimise the transportation logistics of biomass, a break-even distance was introduced in order to determine which transport means in combination with biomass pretreatment is the most efficient from an energy perspective. Results show that torrefaction and pelleting are energetically unfeasible, when comparing the energy use for these pretreatment options, with the energy savings in transportation in the EU.

Opportunities and barriers for large scale biomass gasification in the Dutch residential sector

The Dutch residential sector is largely dependent on the use of low-caloric natural gas for heating purposes, since about 90% of this sector has a connection to the natural gas grid. The expected depletion of national reserves and induced earthquakes in the production area are reasons to aim to escape this lock-in. The Dutch government and key players in the natural gas sector have expressed large green gas ambitions. Hence, green gas is complementary to the existing supply system and therefore suitable to replace natural gas. Introducing green gas on such a large scale would require a suitable technology, such as biomass gasification. However, this technology is still in a developing phase. Therefore, the opportunities and barriers of biomass gasification for green gas production and application in the residential sector were explored.

The Technological Innovation Systems and Multi-Level Perspective were applied as sustainability transition frameworks to explore the current technological state of biomass gasification and the developments in the residential sector. Four limitations were observed from a supply perspective; little financial space for demonstration plants, absence of technology specific policy, lagging market developments and insecurities related to biomass availability. On the demand side, clear barriers hampering change are observed, which provide opportunities for green gas.

Key players in the natural gas regime take no substantial responsibility, despite their potential ability to contribute to overcoming systemic barriers**.**

Therefore, this research concludes that the current green gas ambitions set by the Dutch government are not yet feasible and that the government may address this with technology specific policy, substantial research and development subsidies and funding.

Conclusion

This thesis aimed to explore the potential contribution of three technological innovations, which are, electric vehicles, biomass co-combustion and biomass gasification, to the energy transition. The contribution of these technological innovations to the energy transition is small. There are some positive short term effects, but on the long term these positive effects are annulled. Hence, efficiency increases cannot keep up with continuously increasing demand. Despite European policy expecting a substantial contribution from biomass for energy purposes and electric vehicles, there is no long term effect resulting in an energy transition to a sustainable energy system. This may have potentially dire consequences, since the expected time remaining to implement the required system change and overcome carbon dependency, to prevent the effects of climate change from becoming acute instead of chronic, is about four decades. Biomass gasification technology could theoretically contribute to the energy transition, but diffusion of this technology is in the order of decades and in addition, substantial upscaling is still required. In conclusion, both electric vehicles with lithium based batteries and biomass for energy are still subject to high expectations during the energy transition, which are, as emphasised by this thesis, not feasible. Therefore, the three explored technological innovations have at best, a marginal contribution to the energy transition.

The explored technological innovations can be regarded as incremental innovations. Incremental innovation basically improves that what already exists (i.e. in this case, the energy system) and generally results in more efficient use of resources. European energy policy aims to ensure supply of energy, at affordable cost and introduce renewable energy. These three objectives tend to have incremental innovations as the optimal outcome. For example, co-combustion for electricity contributes to security of supply at a low cost and is more environmentally friendly than coal combustion. This outcome may be the optimal outcome of the three policy objectives, but it does not lead to an energy transition nor to a sustainable energy system. That what already exists (i.e. the energy system) can be regarded as the accumulation of the outcomes of historic decisions. This so-called path dependence, where historic decisions affect future decisions, has led to a state of carbon lock-in. Despite, the clear gains of a successful energy transition, its implementation appears impractical and resolving carbon lock-in with technological innovations alone is therefore not enough. Jevons paradox already showed that the environmental problems related to an increasing population with continuously growing demand cannot be resolved with technology alone. Therefore, in order to have a successful energy transition, other factors, besides technology, that also affect the energy transition, such as economy, politics and its interactions, should be taken into account. The emphasis of policy should not be on the introduction of technology to continue economic growth, but to increase quality of life and decrease consumption and dependency on finite resources. Besides a clear vision on which technologies should be introduced, other factors influencing diffusion of innovations have to change, in order to substantially decrease resource use. Currently, the most important global agreement to address climate change is the Paris Agreement (United Nations, 2015). It literally states, "[a]ccelerating, encouraging and enabling innovation is critical for an effective, long term global response to climate change and promoting economic growth and sustainable development”. Unfortunately, the part about promoting economic growth and sustainable development is not an oxymoron, but a contradictio in terminis, given the finite amount of resources available. Given the timeframe that remains to introduce the required change, in order to have a successful energy transition, substantial change should not be expected from technological innovation alone. Therefore, not only should a clear vision be developed on a European level addressing the design of a sustainable energy system from a technological perspective, but also how the energy transition towards this sustainable system should be realised from an institutional and infrastructural perspective.

Samenvatting

Biomassa of batterijen: de rol van drie technologische innovaties in de energietransitie


LOADLOCATION
UITSLUITEND
ELEKTRISCHE
VOERTUIGEN

Introductie

De mens staat aan de vooravond van een energietransitie, waarin de samenleving moet omschakelen van een afhankelijkheid van fossiele brandstoffen, naar het gebruik van hernieuwbare energie. Momenteel is ongeveer 10% van het finale energiegebruik afkomstig van moderne hernieuwbare energiebronnen. Het doel van het in Parijs gesloten klimaatakkoord is om de gevolgen van klimaatverandering tegen te gaan, door de stijging van de globale temperatuur gemiddeld onder de 2°C te houden. Gezien de huidige uitstoot van broeikasgassen en het resterende koolstofbudget, zou er vanaf nu een lineaire daling moeten worden gerealiseerd naar nul emissies in 2060, om een succesvolle energietransitie te realiseren. Naast het verkleinen van de gevolgen van klimaatverandering, door het verminderen van de uitstoot van broeikasgassen, is er een tweede argument om de energietransitie te organiseren, namelijk de uitputting van hulpbronnen. Recente schattingen voor de verhouding van reserves ten opzichte van productie, voor olie, aardgas en steenkool zijn respectievelijk 50, 52 en 153 jaar. Ondanks de duidelijke argumenten voor een energietransitie, namelijk het tegengaan van klimaatverandering en de reductie van de afhankelijkheid van eindige hulpbronnen, is een dergelijke transitie geen eenvoudige opgave.

Een energietransitie vereist systeemverandering. Hier wordt systeemverandering beschouwd als de verandering naar een duurzaam energiesysteem, waarbij de huidige koolstofafhankelijkheid wordt overwonnen. Dit is een duidelijke uitdaging, omdat geïndustrialiseerde landen verslaafd zijn aan fossiele brandstoffen om voortdurende economische groei en toenemende consumptie te kunnen realiseren. Het huidige energiesysteem, gebaseerd op fossiele koolstof, is zodanig complex dat de combinatie van, en de interactie tussen technologische, institutionele en maatschappelijke factoren systeemverandering belemmert; dit wordt ook wel de koolstof lock-in genoemd. De uitdaging van systeemverandering kan beter worden begrepen met het concept padafhankelijkheid dat uiteindelijk heeft geleid tot de koolstof lock-in. Het bestaande, op koolstof gebaseerde, energiesysteem kan worden beschouwd als het resultaat van de accumulatie van historische beslissingen. Deze historische beslissingen beïnvloeden toekomstige beslissingen, onafhankelijk van de huidige relevantie van deze historische omstandigheden. De accumulatie van historische beslissingen, gerelateerd aan de ontwikkeling van het energiesysteem, is gedreven door rendementsvergroting, door middel van schaalvergroting en heeft geleid tot de huidige koolstof lock-in.

Van een aantal factoren is bekend dat ze systeemverandering beïnvloeden, waarvan beleid als een belangrijke factor wordt beschouwd. De Europese Unie (EU) wil een rol spelen bij het begeleiden van de energietransitie. Dit blijkt uit diverse energiebeleidsnota's en de ratificatie van het Parijs Akkoord. Innovatie speelt een sleutelrol in het beleid van de EU en bovendien zijn de verwachtingen voor de rol van technologie in de energietransitie hooggespannen.

Het is echter de vraag of technologische innovatie voldoende is om de uitdagingen van klimaatverandering en uitputting van hulpbronnen binnen het resterende tijdsbestek op te lossen. Daarom is het voornaamste doel van dit proefschrift om de potentiële bijdrage van drie technologische innovaties aan de energietransitie te onderzoeken. Er worden casussen bestudeerd die zich richten op twee cruciale materialen, namelijk lithium en biomassa, en drie belangrijke sectoren, namelijk privaat vervoer, energieproductie en de huishoudsector.

Lithium beschikbaarheid in de Europese Unie voor elektrische auto's

De negatieve gevolgen van klimaatverandering worden algemeen erkend, evenals het belang van de beperking van de uitstoot van koolstofdioxide (CO_2). Daarom zijn de verwachtingen van elektrische auto's hooggespannen, omdat het gebruik hiervan de uitstoot van broeikasgassen kan doen verminderen en diens efficiëntie hoger is dan bij conventionele voertuigen. Daarnaast hebben deze voertuigen geen uitlaatemissies. Lithium-ion (Li-ion) batterijen lijken de meest veelbelovende, doordat ze een hoge energiedichtheid hebben. De huidige uitdaging is de benodigde toename van het tempo waarmee lithiumcarbonaat (Li_2CO_3) beschikbaar moet zijn in de maatschappij, om zo de voorspelde groei van de elektrische voertuigen vloot te kunnen realiseren.

Door onderzoek zijn tien factoren bepaald die de beschikbaarheid van Li-ion batterijen voor de EU in de komende decennia beïnvloeden. Deze factoren zijn meegenomen in een dynamische systeem analyse, waarbij voorraden, stromen en terugkoppelingen in het systeem geanalyseerd werden. De resultaten van dit onderzoek tonen aan dat er een tekort aan Li_2CO_3 zal zijn tussen de 0.5 tot 2.8 Mt tot 2045. Substitutie van het gebruik van Li_2CO_3 in andere markten en recycling kan deze druk op de beschikbaarheid van Li_2CO_3 tot op zekere hoogte verlichten. De toename van het tempo waarmee Li_2CO_3 geproduceerd kan worden blijkt volgens de berekeningen beperkt en daarom kan met het beschikbare Li_2CO_3 slechts 20% van het wagenpark in de EU in 2050 uit elektrische auto's bestaan. Het gebrek aan Li_2CO_3 in de EU en de geografische spreiding van Li_2CO_3 in politiek gevoelige gebieden suggereren dat het beschikbare aandeel Li_2CO_3 voor de EU zelfs kleiner kan zijn dan in dit onderzoek is aangenomen.

Een alternatieve toepassing van het beschikbare Li_2CO_3 is in de vorm van plug-in hybride voertuigen (PHEV). Deze voertuigen vereisen minder Li_2CO_3 en daarom is een 100% PHEV scenario haalbaar in 2050. Dit zou resulteren in een substantiële afname van de emissies van het gehele wagenpark ten opzichte van het 20% volledig elektrische scenario. Dit heeft een positief effect op klimaatverandering, maar het draagt niet bij aan een afname van de koolstofafhankelijkheid, omdat PHEV op koolstof gebaseerde brandstoffen nodig blijven hebben. Daarnaast zorgt een dergelijk scenario ervoor dat de gevolgen van klimaatverandering verder naar de toekomst verplaatst worden, waardoor het niet leidt tot een oplossing voor de bestaande problematiek.

De toename van het tempo waarmee Li_2CO_3 beschikbaar wordt in de maatschappij is de sleutel voor een overgang naar volledig elektrische auto's in de EU, tenminste wanneer Li-ion batterijen worden toegepast. De grootschalige toepassing van volledig elektrische auto's met Li-ion batterijen, om de CO_2 uitstoot in het vervoer en de afhankelijkheid van vloeibare fossiele brandstoffen te verminderen, is daarom niet gegarandeerd.

Biomassa bijstook in een kolencentrale

In de vorige eeuw is de verbranding van kolen op grote schaal toegepast voor de opwekking van elektriciteit. Het is bekend dat steenkool de meest vervuilende fossiele brandstof is. Desondanks zijn de lock-in effecten van kolengestookte energiecentrales toegenomen als gevolg van goedkope emissiecertificaten, lage kolenprijzen en deregulering van de Europese energiesector. Er is een verscheidenheid aan technologische innovaties beschikbaar om de milieueffecten van steenkoolverbranding te verminderen, zoals het afvangen en opslaan van CO_2, het verhogen van de efficiëntie van de ketel en de bijstook van biomassa met steenkool. In dit proefschrift is de bijdrage aan het tegengaan van klimaatverandering met behulp van biomassa bijstook onderzocht. Een aantal verschillende aanvoerketens werden geanalyseerd voor een variatie aan bijstookscenario's in een kolencentrale. Deze scenario's zijn beoordeeld op indicatoren uit de richtlijn hernieuwbare energie, namelijk energie-efficiëntie, energiegebruik, productie van hernieuwbare energie en uitstoot van broeikasgassen, om vervolgens vergeleken te worden met een volledig kolengestookt scenario. In de scenario's zijn de bijgestookte percentages biomassa 10%, 25% en 60%. Vervolgens is er voor al deze percentages gekeken naar de prestatie van biomassa in vier verschillende vormen, namelijk houtsnippers, pellets, getorreficeerde houtsnippers, en een combinatie van getorreficeerd en gepelletiseerd (TOP) hout.

De 60% bijstookscenario's voor biomassaverbranding in de keten laten zien dat de emissies van broeikasgassen met 48% gereduceerd kunnen worden, ervan uitgaande dat biomassa koolstofneutraal is. De lage bijstookscenario's zijn effectief om de uitstoot van broeikasgassen te verminderen, maar de marges zijn echter minimaal. Momenteel is de bijstook van pellets de norm, maar de verbranding van TOP vertoont de beste resultaten. Daarbij moet wel in acht genomen worden dat de resultaten van TOP ook het meest speculatief zijn. Naast deze resultaten lieten de verschillende scenario's zien dat de indicatoren uit de richtlijn hernieuwbare energie van de EU, die het gebruik van energie uit hernieuwbare bronnen wil stimuleren, niet op elkaar kunnen worden afgestemd. Een voorbeeld hiervan is dat de uitstoot van broeikasgassen in alle scenario's afneemt, maar dat het totale energiegebruik stijgt.

Concluderend laten de resultaten zien dat wanneer de beschikbaarheid van biomassa als schaars wordt beschouwd, bijstook van kleine aandelen biomassa of geen bijstook de beste opties zijn, vanuit een energieperspectief. Wanneer de beschikbaarheid van biomassa als overvloedig wordt beschouwd, is de bijstook van grote aandelen biomassa de beste optie vanuit het oogpunt van broeikasgasreductie.

Ketenanalyse van biomassavergassing voor de productie van groen gas

Houtachtige biomassa kan worden verbrand samen met steenkool, maar een alternatieve toepassing is een thermisch-chemische omzetting naar een groen gas, met behulp van biomassavergassingstechnologie. Dit groene gas heeft eigenschappen die vergelijkbaar zijn met aardgas, waardoor het geschikt is voor injectie in het bestaande distributienetwerk. Een kwart van de totale vraag naar primaire energie wordt in de EU vervuld met aardgas, hetgeen kansen biedt voor de grootschalige toepassing van groen gas via de biomassavergassingsroute. Groen gas dat wordt geproduceerd door vergassing van biomassa kan bijdragen aan een duurzamer energiesysteem, aangezien de uitstoot van broeikasgassen kan worden verminderd. De prestaties van de mogelijke grootschalige toepassing van biomassavergassing voor de productie van groen gas moeten worden bepaald aan de hand van een ketenanalyse, waarbij productie, conversie en toepassing inbegrepen zijn. Om de energieprestatie en het broeikasgasreductie potentieel te vinden van biomassavergassing, is er een ketenanalyse van groen gas routes uitgevoerd. Een verscheidenheid aan scenario's werd bestudeerd, waarbij houtsnippers, pellets en getorreficeerd hout werden meegenomen. Er is een model ontworpen om de prestaties van biomassa naar groen gas te analyseren en de impact van 1% groen gas in het energiesysteem in te schatten. Deze 1% vertegenwoordigt 0.25% van de primaire energievraag in de EU.

De resultaten laten zien dat een vermindering van de uitstoot van broeikasgassen met bijna 70% mogelijk is, met de inzet van 1.3 Mha landbouwgrond. Om het gebruik van aardgas in de EU te vervangen door groen gas zou 140% van de momenteel in gebruik zijnde landbouwgrond nodig zijn. Dit benadrukt het risico van een aankomende importafhankelijkheid van buiten Europa, wanneer een dergelijk systeem grootschalig toegepast wordt. Om de transportlogistiek van biomassa te optimaliseren zijn de afstanden berekend die vanuit energieperspectief het meest efficiënt zijn voor verschillende types voorbewerkte biomassa met verschillende transportmiddelen. De resultaten laten zien dat de productie van getorreficeerd hout en pellets op de winningslocatie in een zodanig hoog energieverlies of energiegebruik resulteren, dat deze energie niet bespaard kan worden door meer geoptimaliseerd transport binnen de EU.

Kansen en barrières voor grootschalige biomassavergassing voor groen gas in de Nederlandse huishoudens

De Nederlandse huishoudsector is grotendeels afhankelijk van het gebruik van laagcalorisch aardgas voor verwarmingsdoeleinden, aangezien ongeveer 90% van de huishoudens een aansluiting heeft op het aardgasnet. De verwachte uitputting van nationale reserves en geïnduceerde aardbevingen in het productiegebied, zijn redenen om het aardgasgebruik in deze sector drastisch te verminderen. De Nederlandse overheid en belangrijke spelers in de aardgassector hebben grote ambities geuit als het gaat om groen gas gebruik in de toekomst. Groen gas is geschikt als vervanger voor aardgas en kan daarom via het bestaande distributiesysteem aardgas vervangen. De toepassing van groen gas op een dergelijk grote schaal vereist een grootschalige toepassing van specifieke technologie, zoals biomassavergassing. Deze technologie bevindt zich echter nog in een ontwikkelingsfase, hierom werden de ontwikkelingskansen en -barrières voor de productie en toepassing van groen gas in de huishoudsector verkend.

De technologische innovatie systemen en het multi-level perspectief werden toegepast als duurzaamheidskaders voor de verkenning van de huidige technologische staat van biomassavergassing en de mogelijke ontwikkelingen in de huishoudsector. Vier barrières werden waargenomen: weinig ruimte voor demonstratie installaties, geen technologie specifiek beleid, marktontwikkelingen blijven achter en duidelijke onzekerheden gerelateerd aan de toekomstige beschikbaarheid van biomassa. In de huishoudens worden duidelijke barrières waargenomen die veranderingen, die kansen bieden voor groen gas, belemmeren. Belangrijke spelers in het aardgasregime nemen geen substantiële verantwoordelijkheid, ondanks hun potentiële vermogen om bij te dragen aan het overkomen van systeembarrières.

Hierom concludeert dit onderzoek dat de door de Nederlandse overheid gestelde groen gas ambities niet haalbaar zijn. De overheid kan hierop sturen door technologie specifiek beleid, aanzienlijke onderzoeks- en ontwikkelingssubsidies en financiering te implementeren.

Conclusie

In dit proefschrift is gekeken naar de mogelijke bijdrage aan de energietransitie van twee energiedragers (biomassa en Li-ion batterijen), toegepast in drie technologische innovaties. De bijdrage van de bestudeerde innovaties aan de energietransitie is klein. Er zijn enkele positieve korte termijn effecten, maar op lange termijn worden deze tenietgedaan. De oorzaak hiervan is dat de voortdurend groeiende vraag niet gecompenseerd wordt door verbeterde efficiëntie. Ondanks dat het Europese beleid een duidelijke bijdrage verwacht van biomassa voor energiedoeleinden en elektrische voertuigen, is er geen lange termijn effect dat resulteert in een energietransitie naar een duurzaam energiesysteem. Dit kan mogelijk ernstige gevolgen hebben, aangezien de resterende tijd om de fossiele koolstofafhankelijkheid terug te brengen naar nul, ongeveer vier decennia is. Biomassavergassing zou theoretisch kunnen bijdragen aan de energietransitie, maar de benodigde ontwikkeling en diffusie van deze technologie in het energiesysteem is in de orde van tientallen jaren, waarin er aanzienlijke opschaling van de technologie nodig is. In conclusie, zowel elektrische voertuigen met op lithium gebaseerde batterijen als biomassa voor energie zijn nog steeds onderhevig aan hoge verwachtingen tijdens de energietransitie, die, zoals gedemonstreerd in dit proefschrift, niet haalbaar zijn. Hierom leveren de drie bestudeerde technologische innovaties in het beste geval een marginale, maar geen structurele bijdrage aan de energietransitie.

De onderzochte technologische innovaties kunnen worden beschouwd als incrementele innovaties. Incrementele innovatie verbetert in zijn algemeenheid datgene wat reeds bestaat (i.e. het bestaande energiesysteem) en resulteert daarom over het algemeen in meer efficiënt gebruik van hulpbronnen. Het Europese energiebeleid is erop gericht de levering van energie te garanderen tegen betaalbare kosten en hernieuwbare energie te introduceren. Deze drie doelstellingen leiden ertoe dat incrementele innovatie de optimale uitkomst is. Bijstook van biomassa in een kolencentrale leidt tot hoge leveringszekerheid met lage kosten en is milieuvriendelijker dan enkel het stoken van kolen. Dit resultaat kan een optimale uitkomst zijn van de Europese doelstellingen van het energiebeleid, maar leidt niet tot de beoogde energietransitie noch een duurzaam energiesysteem. Het bestaande energiesysteem kan worden beschouwd als de accumulatie van de uitkomsten van historische besluiten. Deze zogenaamde padafhankelijkheid, waarbij historische besluiten van invloed zijn op toekomstige besluiten, heeft geleid tot een toestand van koolstof lock-in. Ondanks de duidelijke voordelen van een succesvolle energietransitie, lijkt de uitvoering ervan onpraktisch. Het tot stand brengen van de energietransitie met alleen technologische innovatie is duidelijk niet voldoende. Jevons paradox liet al zien dat de milieuproblemen, gerelateerd aan een groeiende bevolking met een voortdurend stijgende vraag, niet met technologie alleen kunnen worden opgelost. Daarom moeten er, met het oog op een succesvolle energietransitie, ook andere factoren aangepakt worden naast technologie, zoals economie, gedrag, politiek en de interacties tussen deze factoren. De nadruk van het beleid moet niet liggen op de introductie van technologie om de economische groei voort te zetten, maar om de kwaliteit van leven te verhogen en de consumptie en afhankelijkheid van eindige hulpbronnen te verminderen. Naast een duidelijke visie op welke technologieën dienen te worden geïntroduceerd, is het nodig dat andere factoren die invloed hebben op de diffusie van technologische innovaties aangepast worden, zodat ze bijdragen aan het substantieel verminderen van het gebruik van eindige hulpbronnen. Momenteel is de belangrijkste overeenkomst om klimaatverandering aan te pakken het Parijs Akkoord uit 2015. Dit stelt letterlijk dat "het versnellen, aanmoedigen en faciliteren van innovatie van cruciaal belang is voor een effectieve, wereldwijde lange termijn respons op klimaatverandering en het bevorderen van economische groei en duurzame ontwikkeling". Helaas is het deel over het bevorderen van economische groei en duurzame ontwikkeling geen oxymoron, maar een contradictio in terminis, gezien de beperkte hoeveelheid beschikbare hulpbronnen. Gegeven het tijdpad dat resteert, om de vereiste verandering te introduceren voor een succesvolle energietransitie, moet substantiële verandering niet verwacht worden van alleen technologie. Daarom is er niet alleen een duidelijke visie nodig op Europees niveau over het ontwerp van een duurzaam energiesysteem vanuit een technologisch oogpunt, maar ook hoe de energietransitie naar een duurzaam systeem gerealiseerd zou moeten worden vanuit een institutioneel en infrastructureel perspectief.

About the author

Jan Hessels Miedema was born in Leeuwarden on September the 12th 1985. He did a bachelor in Environmental Science at the Van Hall Instituut, University of Applied Sciences, between 2005 and 2008. In 2011 he completed the master Energy and Environmental Sciences at the University of Groningen. He started his PhD at the Centre for Energy and Environmental Sciences in April 2012 and is expected to obtain his PhD degree in January 2019. Since 2016, he is working as a lecturer in Environmental Physics at the Hogeschool Van Hall Larenstein, University of Applied Sciences in Leeuwarden.

During his PhD trajectory he took a variety of short term courses, such as *Environmental Data Quality* at the University of Twente, organised by the research school for Socio-Economic and Natural Sciences of the Environment (SENSE), and *Publishing in English* in 2014 and *Teaching for PhD students* in 2015, at the Groningen Graduate School of Science. Besides that, he participated in the Groningen Energy Summer School 2013, *A multi-disciplinary approach to energy transition, from policy to physics*. Furthermore, he published four papers in peer reviewed scientific journals, from 2013 to 2018, and presented his research at two international conferences in 2014 and 2015.

Scientific contributions

Publications during the PhD project

Miedema, J. H., & Moll, H. C. (2013). Lithium availability in the EU27 for battery-driven vehicles: The impact of recycling and substitution on the confrontation between supply and demand until 2050. Resources Policy, 38(2), 204-211.

Miedema, J. H., Moll, H. C., & Benders, R. M. J. (2016). Environmental and energy performance of the biomass to synthetic natural gas supply chain. Journal of Sustainable Development of Energy, Water and Environment Systems, 4(3), 262-278.

Miedema, J. H., Benders, R. M. J., Moll, H. C., & Pierie, F. (2017). Renew, reduce or become more efficient? The climate contribution of biomass co-combustion in a coal-fired power plant. Applied Energy, 187, 873-885.

Miedema, J. H., van der Windt, H. J., & Moll, H. C. (2018). Opportunities and barriers for biomass gasification for green gas in the Dutch residential sector. Energies, 11(11), 2969.

Presentations at international conferences

Environmental and energy performance of the biomass to synthetic natural gas supply chain. 9th Conference on Sustainable Development of Energy, Water and Environment Systems, 20-27 September, 2014, Venice, Italy to Istanbul, Turkey.

Gasification technology in the waste treatment cascade as part of a sustainable energy transition. International Society for Industrial Ecology, 07-10 July, 2015, Guildford, England.

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The SENSE Research School declares that **Jan Hessels Miedema** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 40.6 EC, including the following activities:

SENSE PhD Courses

- Environmental Data Quality (2012)
- Environmental research in context (2015)
- Research in context activity: 'Designing and executing clarifying video for a general audience on challenges for energy production and the use of biomass, based on PhD research' (2018)

Other PhD and Advanced MSc Courses

- Groningen Energy Summer School, University of Groningen (2013)
- Publishing in English, GGSS University of Groningen (2014)
- Teaching for PhD students, GGSS University of Groningen (2015)
- PowerPoint, University of Groningen (2015)

Management and Didactic Skills Training

- Supervising BSc student with thesis entitled 'Biofuels in the EU27: Biofuel production potentials in the EU27 in relation to the Renewable Energy Directive '(2014)
- Teaching in the MSc course 'Systems Integration and Sustainability' (2015)
- Teaching in the BSc course 'Energy from Gas' (2015-2017)

Oral Presentations

- *Lithium for batteries*. Energy and Sustainability Research Institute Groningen Symposium, 5 March 2013, Groningen, The Netherlands
- *Environmental and energy performance of the biomass to synthetic natural gas supply chain.* Conference on Sustainable Development of Energy, Water and Environment Systems, 20-27 September 2014, Venice, Italy and Istanbul, Turkey
- *Gasification technology in the waste treatment cascade as part of a sustainable energy transition*. International Society for Industrial Ecology, 7-10 July 2015, Guildford, England

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